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FLEXURE STRENGTH OF ADVANCED CERAMICS - A ROUND ROBIN EXCERISE

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CERAMICS RESEARCH BRANCH

July 1989

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ABSTRACT

A mechanical testing round robin exercise was performed under the auspices of The Technical Cooperation Program (TTCP). TTCP is a collaboration between the defense establishments of Australia, Canada, New Zealand, the United Kingdom, and the Unites States. TTCP coordinates and shares results from research activities. The work reported was performed by panel P-TP-2, Ceramic Materials, and was concluded in 1987.

Flexural strength at room temperature was measured for a sintered alumina and a reaction-bonded silicon nitride. These tests are relevant to advanced structural ceramics. The goal of the exercise was to determine if accurate and consistent results could be obtained by the participants using various test procedures.

The round robin was a success, and most issues raised were unequivocally answered. The sintered alumina and reaction-bonded silicon nitride were quite satisfactory for the exercise. Flexure strengths measured by seven laboratories using the U.S. Army MIL-STD-1942 procedure were, for the most part, quite consistent. A specimen configuration with a 2:1 cross-section ratio also gave good results. Older practices and procedures gave less consistent, and possibly erroneous, results.

CONTENTS

INTRODUCTION

The Technical Cooperation Program (TTCP) P-TP-2 members have, at various times, conducted flexural testing of advanced ceramics. An issue which has been unclear for many years was whether these results were consistent and comparable between laboratories, since different test methods and procedures had been used. Indeed, this is not merely a potential problem with TTCP parties, but is of concern to the entire international advanced ceramics community. The U.S. Army developed a standard for flexure testing in 1983 [MIL-STD-1942 (MR)],[1] and actively propounded its usage. Considerable controversy ensued over the standard. On August 16, 1984, a TTCP P-TP-2 meeting was held at the IIT Research Institute. It was decided that the panel could work together to resolve some of the issues, and that a round robin testing exercise was appropriate. It was decided to test two materials, a sintered aluminum oxide made commercially in the United States, and a reaction-bonded silicon nitride (RBSN) fabricated by the Admiralty Research Establishment (ARE). An ambitious test matrix was prepared which included a variety of testing procedures and specimen sizes. The initial program even incorporated limited high temperature and biaxial disk testing.

Preliminary experiments were then performed by the U.S. Army Materials Technology Laboratory (MTL), the U.S. Naval Research Laboratory (NRL), and the Admiralty Research Establishment. These preliminary experiments verified that the two materials were suitable for the round robin, and uncovered minor problems prior to a large commitment of money and work. Extra bend fixtures were prepared by MTL in accordance with MIL-STD-1942 to loan to panel members, as required.

A lot of 800 alumina specimens were ordered by MTL, however, these were severely damaged by the machining process (more than half of the specimens failed from machining damage related defects). The panel met in London, in July, 1985, and progress was reviewed. It was decided to prepare an entirely new lot of alumina specimens. Limited results from NRL and MTL on the good preliminary lot of alumina were reviewed. Old fixtures and test procedures were shown to give results inconsistent with the MIL-STD-1942 procedure.

A new lot of 13 alumina tiles, sized 4" x 4" x 1", was ordered from the manufacturer in March, 1985. Manufacturing difficulties delayed the receipt of this material until September, 1985. A partial shipment of four tiles was set aside and not used in the main round robin for fear of there being a batch-to-batch variability. These were utilized for an independent study of the machining tolerances of flexure specimens. A reliable vendor was used to machine 720 new alumina specimens, and these were distributed to the participants in November, 1985. A supplemental lot of disk specimens was delivered to Dr. Godfrey of the ARE at this time.

Meanwhile, the RBSN specimens were being meticulously fabricated at the Admiralty Research Institute. In November, 1985, Dr. Godfrey distributed 540 specimens.

In 1985 and 1986, TTCP participants expanded to include the Ontario Research Foundation (ORF) in Canada, the National Physical Laboratory (NPL) in the United Kingdom, and the Materials Research Laboratory (MRL) in Australia. The complete list of TTCP participants, and their points of contact, is given in Table 1. These participating laboratories will, hereinafter, be referred to by their acronyms.

1. U.S. Army military standard, MIL-STD-1942 (MR). *Flexural Strength of High Performance Ceramics at Ambient Temperature*, November 1983.

Table 1. PARTICIPATING LABORATORIES

Laboratory	Point of Contact
U.S. Army Materials Technology Laboratory (MTL)	Mr. George D. Quinn
U.S. Navy Naval Research Laboratory (NRL)	Dr. David Lewis
U.S. Air Force Wright Aeronautical Laboratory (AFWAL)	Dr. Norman Tallan and Dr. Robert Ruh
Testing Performed on Behalf of AFWAL by: IIT Research Institute	Mr. Silvester Bortz, Mr. David Larsen, Ms. Jane Adams, and Ms. Sharon Stuckley
Her Majesty's Admiralty Research Establishment, U.K. (ARE)	Dr. David Godfrey
National Physical Laboratory, U.K. (NPL)	Dr. Roger Morrell
Canadian Department of National Defense	Dr. C. Gardner, DRDA
Testing Performed on Behalf of DRDA by: Ontario Research Establishment (ORF)	Dr. J. Sullivan and Dr. P. Lauzon
Australian Department of Defense Materials Research Laboratory (MRL)	Mr. Graham Johnston

The issues which the main TTCP round robin was intended to resolve are listed in Table 2. These issues will be addressed, individually, in the Results Section of this report.

All testing on the main TTCP round robin was performed in 1986 and early 1987. The final test matrix is shown in Table. 3. The IITRI effort was one of the last undertakings by the ceramics group prior to its dissolution in 1986. On the other hand, the ORF and MRL efforts were among the first in the field of advanced ceramics.

Table 2.

Key Issues

1. Using a common procedure, can different laboratories measure flexure strength accurately and precisely?
2. Does the 3 mm x 6 mm specimen give satisfactory results relative to the 3 mm x 4 mm configuration?
3. Given a constant specimen size (3 mm x 4 mm), are "old" or "current" test fixtures giving results consistent with MIL-STD-1942 test fixtures?
4. Are "old" or "current" practices (different fixture and specimen sizes) giving results comparable to MIL-STD-1942?

Secondary Issues

5. Does a Weibull size analysis apply to the strength data?
6. Does machining the reaction layer off of the RBSN alter the strength?
7. Was humidity a factor?
8. What did fractography reveal?
9. Can different machine shops produce satisfactory flexure specimens?
10. Are there lot-to-lot variations of strength in the material?

Table 3. TEST MATRIX FOR TTCP ROUND ROBIN
(THE SPECIMEN TYPE IS DENOTED BY THE CROSS-SECTION DIMENSIONS.)

Sintered Alumina, Grade AD 999
(35 Specimens Per Condition Were Delivered, 30 to be Tested)

Establishment	Specimen Type 3 mm x 4 mm	3 mm x 6 mm	Other
MTL (Quinn)	4 pt, MIL STD B† 4 pt, MIL STD B	4 pt, MIL STD B	4 pt, MIL STD A 4 pt, MIL STD C
AFWAL/IITRI (Tallan)	4 pt, MIL STD B 4 pt, IITRI Fixt.‡	4 pt, MIL STD B	4 pt, IITRI Fixt., 1/4" x 1/8"
ARE (Godfrey)	4 pt, MIL STD B 3 pt, MIL STD B 4 pt, ARE Fixt. 4 pt, ARE Fixt.		
NRL (Lewis)	4 pt, MIL STD B*	4 pt, MIL STD B*	
NPL (Morrell)	4 pt, MIL STD B 4 pt, NPL Fixt.	4 pt, MIL STD B	
ORF (Sullivan)	4 pt, MIL STD B 3 pt, MIL STD B		
MRL (Johnston)	4 pt, MIL STD B		

Reaction-Bonded Silicon Nitride (RBSN)
(30 Specimens Per Condition)

Establishment	Specimen Type 3 mm x 4 mm As-Fired	3 mm x 4 mm Machined	Other
MTL (Quinn)	4 pt, MIL STD B 3 pt, MIL STD B	4 pt, MIL STD B	
AFWAL/IITRI (Tallan)	4 pt, MIL STD B 4 pt, IITRI Fixt.		
ARE (Godfrey)	4 pt, MIL STD B 3 pt, MIL STD B 4 pt, ARE Fixt. 4 pt, ARE Fixt.		3 pt, ARE Fixt. (4.5 mm x 4.5 mm) 3 pt, ARE Fixt. (4.5 mm x 4.5 mm)
NRL (Lewis)	4 pt, MIL STD B* 3 pt, MIL STD B*		
NPL (Morrell)	4 pt, MIL STD B 4 pt, NPL Fixt.	4 pt, MIL STD B	
ORF (Sullivan)	4 pt, MIL STD B		

*These tests were not performed
†MIL STD Refers to the U.S. Army military standard MIL-STD-1942 (MR), fixture A, B, or C, as defined later in this report
‡Fixt. stands for fixture

OBJECTIVE

The principal goal of the exercise was to compare the experimental results for flexure strength between different test laboratories. These laboratories had used different test methods in the past, and it was unclear whether the results were consistent. The laboratories agreed to test in accordance with their normal practices and, also, for the purposes of a direct comparison, to test in accordance with the U.S. Army MIL-STD-1942 (MR). MIL-STD-1942 was developed expressly to bring consistency and accuracy to flexure testing of advanced ceramics. Both 3- and 4-point testing were performed in this round robin, with a variety of specimen sizes. A suggested modification to MIL-STD-1942, to incorporate a 2:1 cross-section aspect ratio specimen, was also used in the testing schedule.

There are three sources of variability for the flexure strength results obtained by the different laboratories:

1. Material nonuniformity (billet-to-billet, or within billet, batch-to-batch, etc.),

2. Test method error or bias, and

3. Inherent statistical scatter due to sampling.

The materials chosen for this round robin were scrutinized to ensure that they were uniform so that the initial consideration could be minimized or eliminated. If there was material nonuniformity, the careful randomization (riffling) of specimens should have eliminated any variability (except when dealing with specimens of one particular size, cut out of one particular portion of one particular billet).

The flexure strengths of a group of brittle ceramic specimens will vary due to the presence of flaws in the material. Flexure strengths are analyzed by the well known Weibull statistics. The strength of both the alumina and the silicon nitride were well modelled by simple Weibull two-parameter statistics. The statistical interpretations of this study were deliberately kept as simple as possible in the interest of not obscuring the key issues, and to provide engineers with a straightforward and easy to understand analysis. It is believed that the analysis is not only adequate, but accurate in the present instance.

All of the results are interpreted only in terms of the Weibull parameters:

m = the Weibull modulus

S_{obb} = the characteristic strength of the bend bar.

(The mean and standard deviation of a set of strength numbers, which are pertinent for a normal distribution of strengths, are also included for convenience only, but are not discussed any further in this report.)

The objective of the analysis was to examine the scatter in results of the different laboratories and distinguish it from **variability due to inherent statistical noise**. The Weibull parameters each laboratory obtained from a common experiment were compared and interpreted according to two simple graphs. These graphs illustrate and quantify the **inherent** scatter in Weibull statistics. The experimental scatter observed in the round robin was compared directly to the analytically derived scatter, and if they were comparable, then the round robin results were **considered consistent and successful**. Alternatively, if the experimental variability was too high, a second set of graphs was consulted to assess whether the outlying results really were **extreme and atypical.**

This process will be demonstrated in detail later in this report by an example. The next section outlines the statistical analysis.

STATISTICAL PROCEDURE

Let a single trial correspond to a single-strength **specimen** outcome, then a group of specimens (30), all tested under identical procedure, would represent a **sample**. The true distribution parameters for all specimens are the **population** parameters. From the **sample**, it is possible to estimate population parameters, but there will generally be some variability in the sample estimates due to inherent statistical fluctuations. For example, if the true population Weibull modulus is 10, then any given sample of 30 specimens could give a modulus of 9, or perhaps 11.

A simple, least squares regression analysis was used in this study. It is similar to practices already in use at the laboratories in this round robin. Flexure strengths were ranked in order within a sample, and assigned a probability according to the formula:

$$P = (i - 0.5) / N$$

where P is the probability of failure, i is the i^{th} specimen, and N is the total number of specimens in the sample.

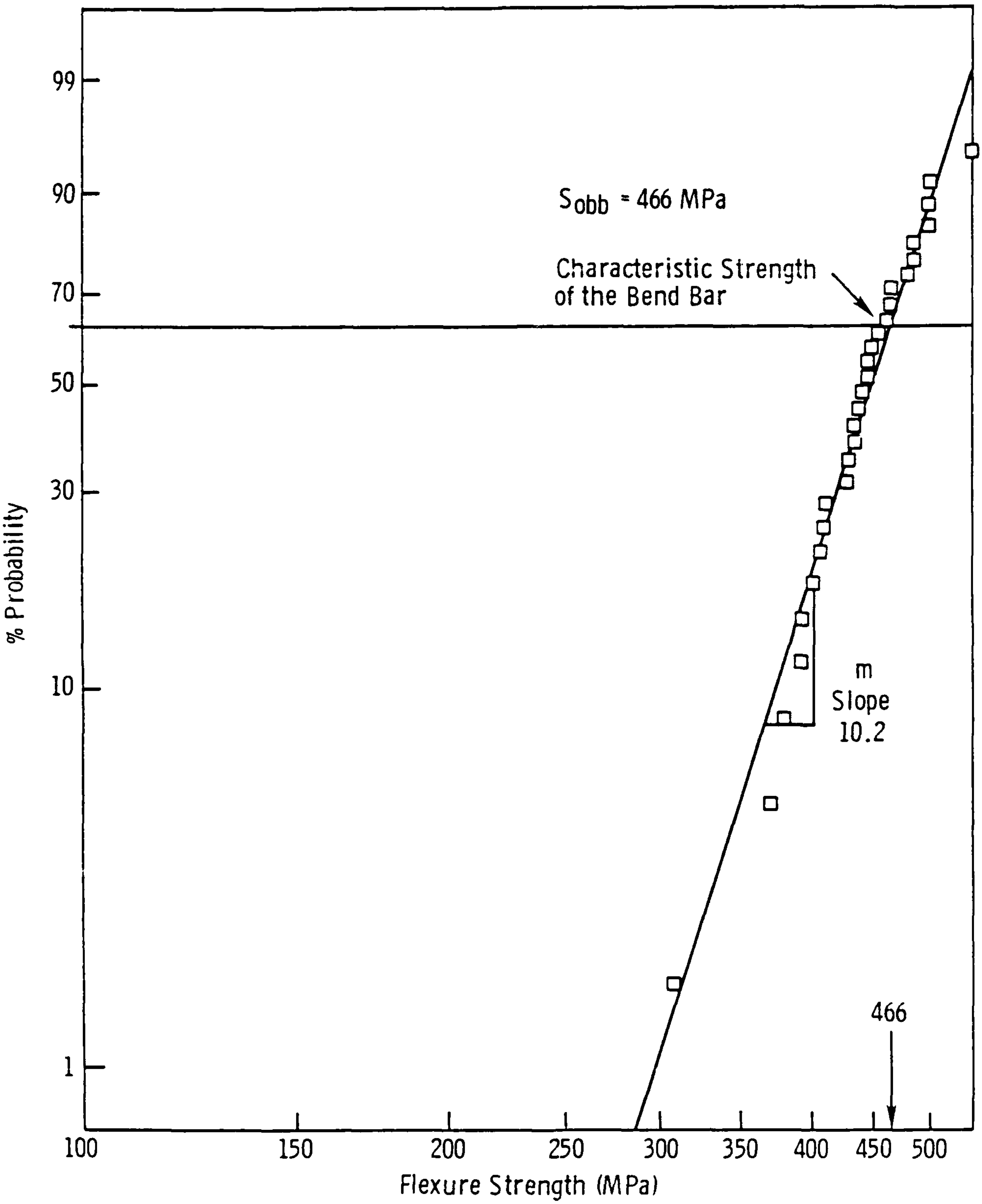
This probability index has been demonstrated to be of low bias (for N >20) and generally superior to other common indicies.[2-4]

The strengths and probabilities were then graphed as shown in Figure 1 where the abscissa is the natural log of stress, and the ordinate ln ln(1/1 - P). The actual stress and probability values are also shown on the axes for convenience. A simple least squares regression line was applied. The Weibull modulus is the slope of the line, and the **characteristic strength of the bend specimen** simply corresponds to the 63.2% probability of failure (1 - 1/exp). (The characteristic strength of the bend bar has not been adjusted in this study to the characteristic strength.) Thus, both the Weibull modulus and the characteristic strength of the bend bar can be readily and visually interpreted on a Weibull graph such as in Figure 1. This representation of the data is commonly used by engineers and scientists due to its simplicity and ease of interpretation.

The "goodness of fit" of the least squares fitted line to the strength data will only be qualitatively assessed in this report. If the data was well fitted by the Weibull graph (a straight line on Figure 1), then the data sample was deemed "well behaved." In a few instances, a stray or outlier strength data (particularly at the low strength end), can have an undue effect upon the curve fitting process. These instances will be discussed as they occur, and outlier data will be deleted as warranted.

There are several papers in the ceramics literature which analyze the typical variability in Weibull parameter estimates due to statistical effects of taking limited sample sizes.[5-8]

2. BERGMAN, B. *On the Estimation of the Weibull Modulus.* J. Mat. Sci. Letters, v. 3, 1984, p. 689-692.
3. JOHNSON, C. *Fracture Statistics of Multiple Flaw Populations* in Fracture Mechanics of Ceramics, v. 5, R. Bradt, A. Evans, D. Hasselman, and F. Lange, ed., Plenum Press, New York, 1983, p. 365-386.
4. TRUSTUM, K. and JAYATILAKA, A. *On Estimating the Weibull Modulus for a Brittle Material.* J. Mat. Sci., v. 14, 1979, p. 1080-1084.
5. RITTER, J. JR., BANDYOPADHYAY, N., and JAKUS, K. *Statistical Reproducibility of the Dynamic and Static Fatigue Experiments.* Ceram. Bull. v. 60, no. 8, 1981, p. 798-806.
6. JOHNSON, C., and TUCKER, W. *Advanced Statistical Concepts of Fracture in Brittle Materials* in Ceramics Technology for Advanced Heat Engines Project, Semiannual Progress Report, October 1985 - March 1986, Oak Ridge National Laboratory, Technical Report ORNL/TM 10079, p. 208-223.
7. McLEAN, A., and FISHER, E. *Brittle Materials Design, High Temperature Gas Turbine.* Interim Report #11, U.S. Army Materials Technology Laboratory, AMMRC TR 77-20, August 1977, p. 111-120.
8. BARATTA, F. *Requirements for Flexure Testing of Brittle Materials.* U.S. Army Materials Technology Laboratory, AMMRC TR 82-20, April 1982, ADA 113937.



99
90
70
50
30
10
1
% Probability
S_{obb} = 466 MPa
Characteristic Strength
of the Bend Bar
m
Slope
10.2
466
100
150
200
250
300
350
400
450
500
Flexure Strength (MPa)

Figure 1.

References 5 and 6 are used **exclusively in this report** since they pertain directly to the Weibull analysis described above; i.e., they treat variability in Weibull estimates when a two-parameter analysis is used, with the probability ranking parameter given above, and with a least squares regression analysis. Indeed, the ceramics literature is evolving towards this common practice for most typical applications. We recognize that it may not necessarily be the most favored by all statisticians, and that it may not be the best for design purposes, however, it is very widely employed by engineers, scientists, and statisticians for preliminary analyses. Other analyses using maximum likelihood estimation (MLE) procedures have been reported elsewhere,[4,7-9] however, these are less familiar to engineers and materials scientists and require more computational effort. Furthermore, for small sample sizes, the MLE method tends to create biased estimates of the Weibull parameters. On the other hand, a desirable aspect of the MLE method is that narrower confidence bands for the Weibull parameters occur for sample sizes greater than 30.[4,6]

(Before continuing any further, it is important to clarify a potentially misleading phrase in Reference 5. The word **sample** in Reference 5 should be changed, for consistency, to **specimen**. Reference 5 uses sample to mean a single test bar. We use sample here to represent a group of bend bars which are a sample of the population.)

We wish to now consider what is the typical, inherent scatter in Weibull parameter estimates, based upon taking a limited size sample; i.e., 30 specimens. We deliberately chose that each sample be composed of 30 specimens since statistical arguments show that the fewer the number of specimens, the poorer the accuracy of the estimates. The value of 30 was chosen as a compromise between good confidence limits and economic considerations. Indeed, improvements in confidence intervals beyond 30 specimens are on a path of diminishing returns.[5-9] References 5 through 9 and MIL-STD-1942 all require or recommend a minimum of 30 specimens per condition.

Ritter et al.[5] demonstrated that the **scatter** in the estimates for the **Weibull** parameters fits a **normal** distribution. Therefore, it is possible to discuss the scatter of values of the Weibull modulus and characteristic strength in terms of the standard deviation, or the coefficient of variation. Ritter et al., discussed the scatter of m value in terms of the coefficient of variation (CV).[5] The coefficient of variation is the standard deviation divided by (or normalized by) the mean value:

$$\mathrm{CV\,(of\ m)} = \frac{\text{standard deviation of m}}{\text{mean value of m}} .$$

Ritter et al.[5] analytically derived curves of CV for both m and S_0, as shown in Figures 2a and 2b. Please note that the scatter in S_0 depends upon the Weibull modulus (or the scatter in strengths), but that the Weibull modulus itself does not. The variance of both parameters is a strong function of the number of specimens in a sample.

The standard deviation of the parameter can be considered the confidence band for 67% of observed scatter; i.e., 67% of outcomes will lie within plus or minus one standard deviation of the mean. In other words, an estimated value of the Weibull modulus m, based upon one sampling, will, 67% of the time, lie within one standard deviation of the true population value. Thus, the curves in Figures 2a and 2b can be interpreted to mean the confidence band for 67% of possible results.

9. BARATTA, F., QUINN, G., and MATTHEWS, W. *Errors Associated with Flexure Testing of Brittle Materials.* U.S. Army Materials Technology Laboratory, MTL TR 87-35, July 1987.

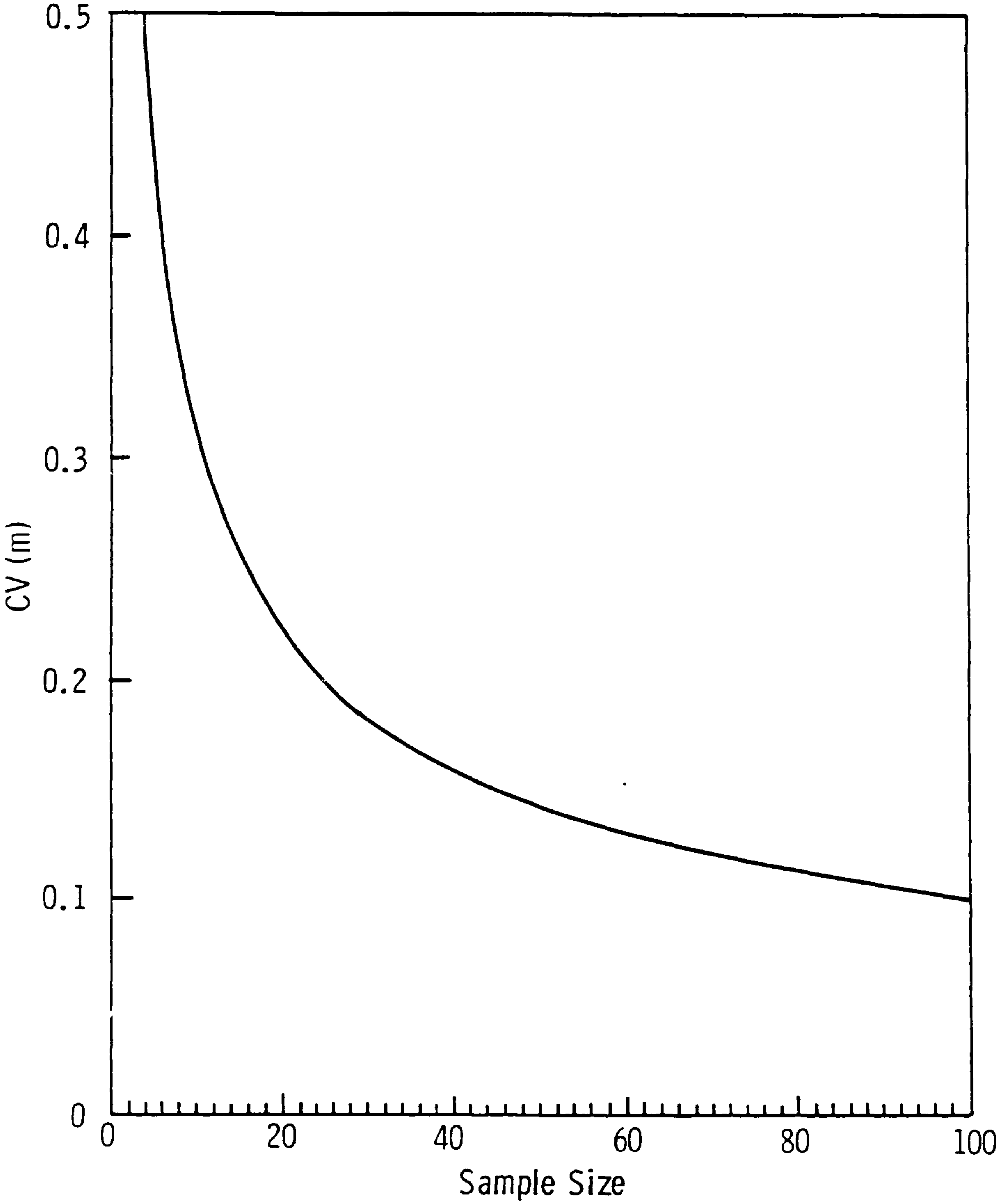
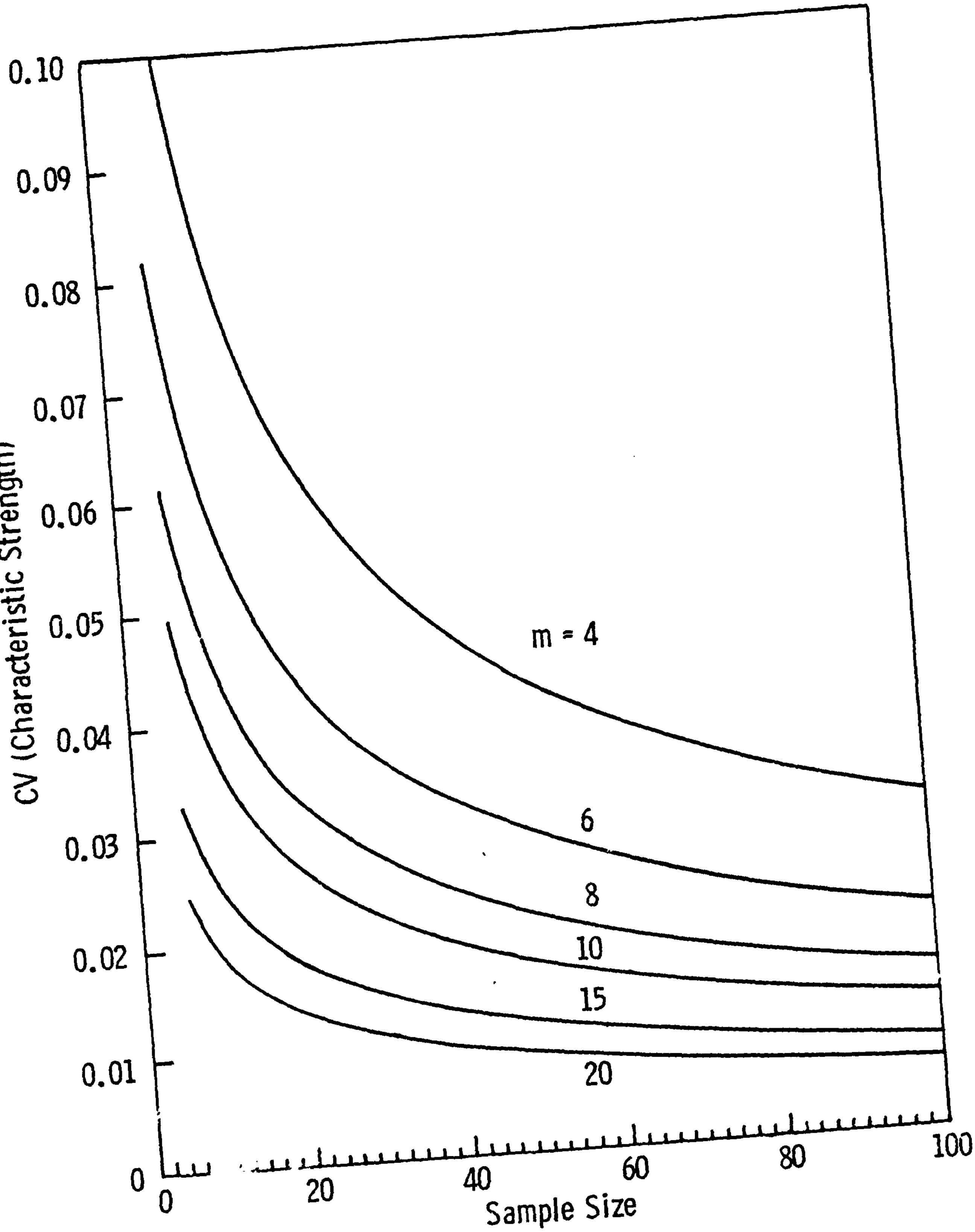


Figure 2a. The coefficient of variation (CV) of the Weibull modulus. Sample size is the number of specimens in one sample. From Reference 5.



F.gure 2b. The coefficient of variation (CV) of the characteristic strength of the bend bar. Sample size is the number of specimens in one sample. From Reference 5.

Johnson and Tucker[6] have also studied the inherent statistical variability due to sampling. They interpreted the scatter in terms of the ratio of the estimated parameter (from a sample) to the true population parameter. For example, for the Weibull modulus m they used the ratio:

$$\frac{m_{est}}{m_{true}}$$

The Johnson and Tucker analysis is for various confidence bounds, however, not merely for the 67% interval. Figures 3a and 3b show the results, and, once again, they are a strong function of sample size. Figure 3a is for all possible m values, but Figure 3b is only for an m of 10. The dotted lines of Figure 3b are reasonable extrapolations of the results of Reference 6 (taking into account the observations of Reference 5 that scatter is normally distributed). Figure 3a shows that for a sample size of 30, the Weibull modulus from a single sampling (m_{est}) should be no more than 1.50 m_{true} for 99% of the time. Similarly, a value of m_{est} lower than 0.63 m_{true} should occur 1% of the time. Thus, the Johnson and Tucker analysis can be used to consider whether a given data sample is "atypical;" i.e., whether the Weibull parameters are unreasonably deviant from the true parameters.

The work of Ritter et al.[5] can be directly compared to the analysis of Johnson and Tucker.[6] The Ritter et al. confidence bounds can be directly superimposed onto the Johnson and Tucker graphs by noting that the 67% confidence interval corresponds to 17% to 83% (net 67% interval) in the Johnson graph. Please note that this can be done since both analyses use least squares regression analysis with the same probability estimators. Thus:

$$\text{CV is:} \quad \frac{\text{67\% confidence band}}{m_{true}}$$

$$= \frac{m_{est} - m_{true}}{m_{true}}$$

where m_{est} is the value of m one standard deviation away from the mean.

The Ritter et al.[5] formulation uses either a mean value of the parameter based upon **estimates from sampling**, or in the analytically derived variance curves, the **population** parameter. As the number of specimens increases, m_{est} will quickly approach m_{true} and this distinction will not matter. This is reflected in Figure 2 of Reference 5 which shows that for a number of specimens greater than 20, the CV behavior based upon Monte Carlo estimates (from taking the mean of samples) converges to the analytically known curve based upon the population parameter. For fewer than 20 specimens, the CV behavior of the sampling (Monte Carlo results) is more scattered than the analytically derived curve because the scatter in observed m values is compounded by scatter in estimates of the mean.

The best estimates of m or S_{obb} will be used in each instance when using Figures 3a and 3b since the true population parameters are unknown. This will usually, but not always, be the mean result for several samples in one set. Of course, as discussed in the previous paragraph, although the mean from a set will converge to the true population parameter, some deviation will exist for small numbers of samples. In practice, this means that some additional variability is to be expected in our experimental work, as compared to the predictions of Figures 3a and 3b.

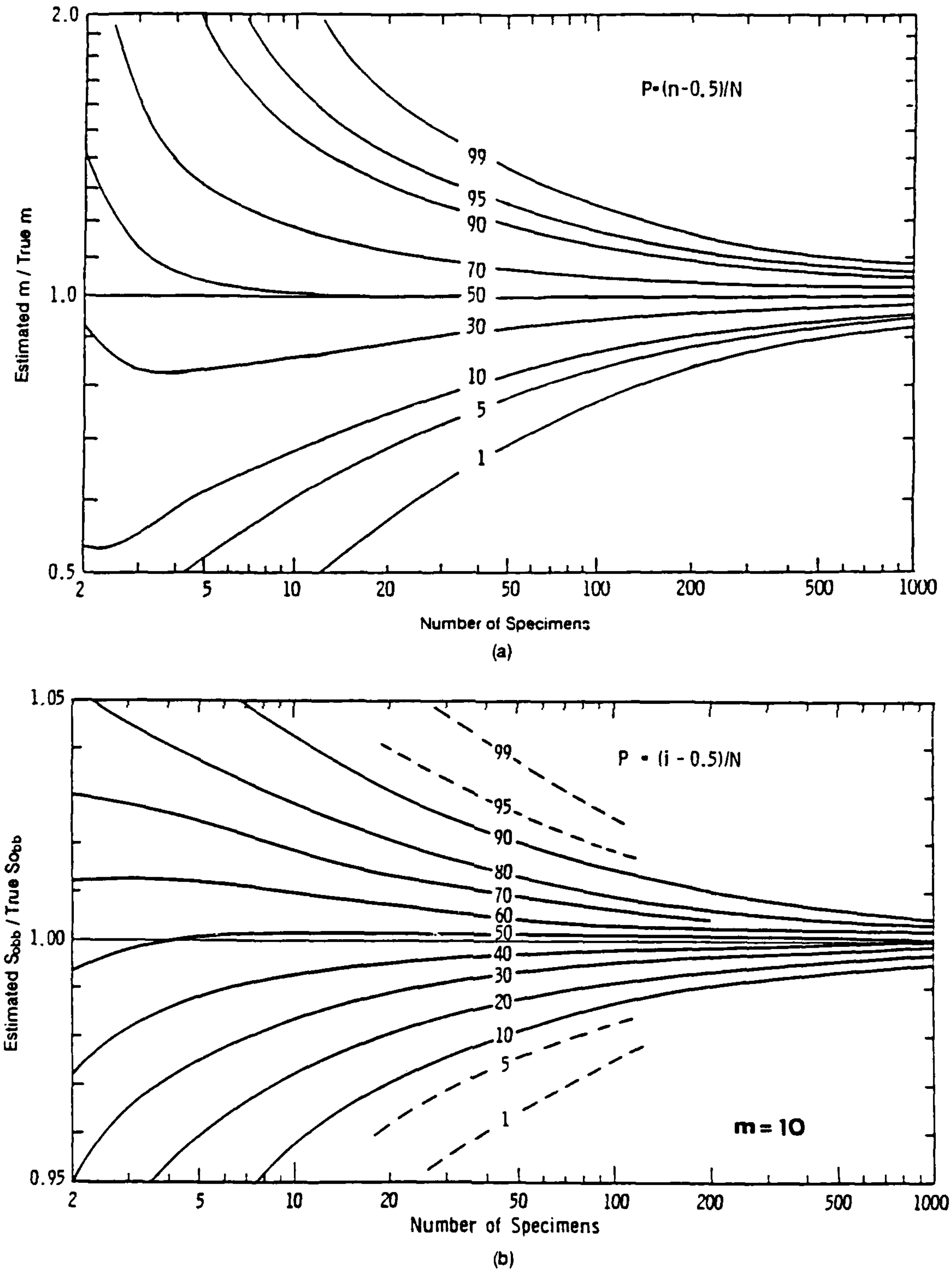


Figure 3. The confidence intervals for Weibull modulus m, and the characteristic strength of the bend bar, S_{obb}. The estimated parameters are derived from a single sample. The confidence bounds for m are shown in (a), and the bounds for S_{obb} are shown in (b). The latter was prepared for an m of 10. From Reference 6.

In summary, the expected variability from statistical scatter due to limited sample sizes has been analyzed in the ceramics literature.[5,6] Figures 2a and 2b will be used to see if the results of several laboratories yield a consistent variance (or coefficient of variation). If the variance is too high, then Figures 3a and 3b will be used to contemplate how deviant the results of a particular sample are.

MATERIALS

Two materials were chosen for the exercise. A sintered alumina available commercially in the United States, Coors grade AD-999,* was chosen due to its low cost, high consistency, fine grain size, high density, and suitability for fractographic examination. The material was sintered and then ground to billets of size 10.16 cm x 10.16 cm x 2.54 cm (4" x 4" x 1"). These billets were very regular in shape, and a bulk density was readily computed for each of the billets. The mean density was 3.968 g/cm^3 with a standard deviation of only 0.004. A detailed ultrasonic "C" scan was performed on one billet. This measures the time of flight of an ultrasonic wave through the billet and is sensitive to density and elastic modulus variations. The test revealed that the material was exceptionally consistent, with variations of the order of tenths of a percent or less. A quantitative impurity analysis revealed the elements in Table 4.

Table 4. ELEMENTS (WEIGHT PERCENT)

C	S	B	Y	K	Fe	Nb	Cr	Si	Ca	Zr	Mg	Ti	Ni	Na
0.084	0.003	<0.01	0.01	<0.01	0.04	0.01	<0.01	<0.01	0.02	0.24	0.09	0.03	0.10	0.01

The alumina was received in three lots. Very careful attention was paid to keeping the groups distinct. The first lot of 10 billets was utilized to prepare a preliminary group of 200 3-mm x 40-mm x 50-mm specimens which were tested at MTL, NRL, and ARE. This was done in order to assess the suitability of this material for a round robin, and to detect any potential testing problems prior to the commitment of large funds and efforts to the main exercise. The preliminary exercise was critical in this regard. The material was found to be satisfactory because it had good consistency, and tended to fail from volume-distributed material flaws (rather than surface machining damage). The preliminary testing did ferret out minor problems as well. Some of the results of the preliminary exercise are shown in Figure 4. Four samples tested in 4-point loading in accordance with MIL-STD-1942, size B[1] (MTL STD B) were in excellent agreement. The CV of m was 0.159, and the CV of S_{obb} was 0.015. Both are **well** within the predicted variances of Figures 2a and 2b for sample sizes of 30.

Strength-limiting defects were readily identified with optical microscopy since fracture mirrors were obvious. Defects were usually pores, porous zones, sintering agglomerates, or inclusions.

*Coors Porcelain Company, Golden, Colorado.

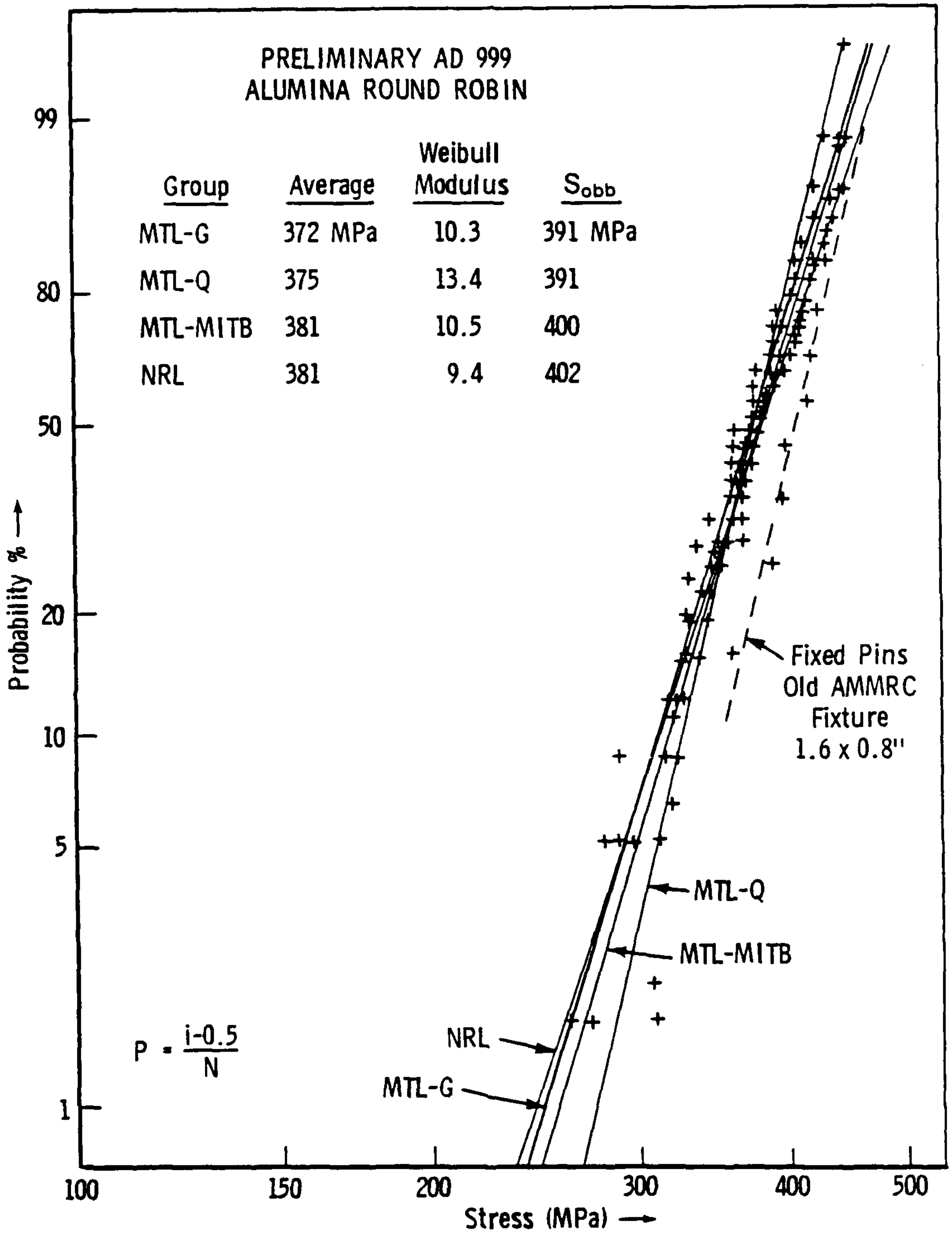


Figure 4. Preliminary test results from 1984 for 3-mm x 4-mm alumina specimens tested in accordance with MIL-STD-1942. Results are very consistent for four samples, three from MTL and one from NRL. The three MTL samples were tested by different operators, on different days, with different fixtures, and with different testing machines. In contrast, a limited sample using the old MTL fixture had a systematic deviation of +13%, which was traced to friction error associated with fixed-loading pins.

The remaining billets were delivered to a vendor to fabricate 800 flexure specimens. The specimens were unsatisfactory when delivered, however, due to excessive machining damage on the surfaces. This damage was in the form of chips, striations, and impacts. Every specimen was painstakingly examined in the hope that some could be salvaged. A group of apparently acceptable specimens was tested, and it was regrettably determined that more than half of these failed from machining damage. The entire lot was then set aside and not used any further.

A new batch of alumina billets was ordered and was received in two shipments; one initial lot of four, and a second lot of nine billets. These lots were kept separate. It was later determined that there might have been a subtle billet-to-billet variation between the two lots. The main round robin exercise was performed with eight of the nine billets of the latter shipment. The initial lot of four billets was used for a parallel study to investigate the ability of vendors to fabricate test specimens. This exercise is described in detail in Reference 10.

The new lot of alumina billets was delivered to a reliable machining vendor and 735 specimens were fabricated. All met the specifications. These specimens were of several sizes. The majority were 3 mm x 4 mm x 50 mm (MIL-STD-1942, size B), some were 3 mm x 6 mm x 50 mm, a single lot of 30 were size 1/8" x 1/4" x 2", and a single lot was made to MIL-STD-1942, sizes A and C. The 3-mm x 6-mm cross-section specimens were made because several members preferred this configuration over the 3 mm x 4 mm, and a direct testing comparison was desired. The 1/8" x 1/4" specimens were made for similar reasons. Finally, the MIL-STD-1942 A and C sizes were made for comparison of results to the B size. **Many times in this report specimen size will be referred to by the cross-section size without specification of length;** i.e., 3 mm x 4 mm or 1/8" x 1/4". Each type of specimen was carefully and thoroughly randomized. Specimens were distributed to the panel members in early November, 1985.

The reaction-bonded silicon nitride (RBSN) was fabricated at ARE by Dr. David Godfrey. A preliminary lot, fabricated in 1984 (batch 2463), proved to be very successful. The specimens were fabricated as individual bend specimens and were not cut out of billets. As such, each specimen had a slight surface-reaction layer that is typical of as-fabricated RBSN. This was a desirable difference relative to the alumina specimens, since it was possible to test both machined and as-fabricated specimens. The dimensional accuracy and appearance of the specimens were impressive in the as-fabricated state. The bulk densities were remarkably consistent; 2.40 g/cm^3 with a standard deviation of only 0.01. The strength-limiting defects are typically volume distributed, unreacted silicon zones, or, alternatively, surface-reaction layer defects. The preliminary specimens had a mean strength of the order of 230 MPa, and a Weibull modulus of 14.

As a result of the successful screening of the preliminary RBSN batch, ARE then proceeded to fabricate an additional three billets in the green state. Two nitridation runs, 2510 and 2511, were then made. From one billet, two samples of 30 specimens sized 4.5 mm x 4.5 mm were made since this was the typical size used by ARE for flexure testing. One sample was nitrided in run 2510; the other in run 2511. Density measurements and comparative 3-point flexure testing at ARE indicated that the two nitridation runs were completely consistent. No further flexure specimens were made from this first green billet.

10. QUINN, G. *Fractographic Analysis and the Army Flexure Test Method* in Fractography of Glasses and Ceramics, J. Varner, and V. Frechette, ed., American Ceramic Society, Ohio, 1988, p. 319-324.

The two remaining billets were then cut into 540 flexure specimens for the main round robin exercise. In run 2510, 240 bars of size 3 mm x 4 mm were nitrided, and 119 were nitrided in run 2511. These 3-mm x 4-mm specimens had very consistent densities, again averaging 2.40 g/cm^3 with a low standard deviation of 0.01. A further 90 oversized 3.5-mm x 4.5-mm specimens were nitrided in run 2511 so that 0.25 mm could be machined off of the surface (bringing the size down to 3 mm x 4 mm) to investigate surface-reaction layer effects. One lot oversized to 0.20" x 0.20" was similarly prepared with the intent to remove the reaction layer. A final lot, 3.68 mm and 6.86 mm (oversized 1/8" x 1/4"), was made to accommodate a request by IITRI. The specimens within a type were randomized, and the lots of 30 specimens were distributed by ARE in November, 1985.

Over 2,000 specimens were prepared for this exercise. In all, 735 alumina and 540 RBSN flexure specimens were actually used in the main round robin exercise. Two hundred additional alumina, and at least 31 RBSN specimens, were prepared for the preliminary phase. An additional 725 alumina specimens were prepared, but not used due to excessive machining damage. Finally, several hundred RBSN or alumina disk specimens and 80 alumina flexure specimens were made for parallel studies at ARE and MTL. (The latter are not discussed in this report.)

FLEXURE TEST METHODS

All testing was performed at ambient room temperature conditions. Three- and 4-point tests were performed on both materials. Each laboratory had the option to test in accordance with their typical (current) practice and, also, with MIL-STD-1942 (MR), which was the common method used by all laboratories. The details of each of the laboratories' current practices have been published elsewhere, and only brief details are included here. Table 3 lists the actual testing performed by each laboratory. The table lists the work by laboratory, by specimen type, and by fixture type. The MIL STD B configuration calls for a 3-mm x 4-mm cross-section specimen, but several lots were tested with alternative specimen sizes, including a 3-mm x 6-mm section specimen.

MIL-STD-1942 (MR), published in November, 1983, was developed to reduce experimental error, enhance data reproducibility and consistency and, ultimately, make flexure data potentially useful for design. The standard was developed for monolithic or simple advanced composite ceramics. With suitable precautions, it can be utilized for high temperature testing as well. MIL-STD-1942 permits three different specimen sizes and either a 3- or 4-point mode of loading. This flexibility was necessary since no one size or test configuration will meet the diverse needs of the advanced ceramics community. The testing configurations and specimen sizes are shown in Figure 5. One critical aspect of MIL-STD-1942 is that it requires that the loading pins be free to rotate in order to eliminate undesirable friction constraints that can cause experimental errors of the order of 10% to 20%. MIL-STD-1942 and supporting documentation[11,12] are available from the U.S. Army Materials Technology Laboratory and the Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, PA 19120-5099.

MTL primarily tested with MIL-STD-1942 procedures, although in the preliminary phase, a 0.8" x 1.6", 4-point flexure fixture with fixed loading pins was used. It was determined that

11. QUINN, G., BARATTA, F., and CONWAY, J. *Commentary on U.S. Army Standard Test Method for Flexural Strength of High Performance Ceramics at Ambient Temperature.* U.S. Army Materials Technology Laboratory, AMMRC TR 85-21, August 1985, ADA 160873.
12. QUINN, G. *Properties Testing and Materials Evaluation.* Cer. Eng. and Sci. Proc., v. 5, no. 5-6, 1984, p. 298-311.

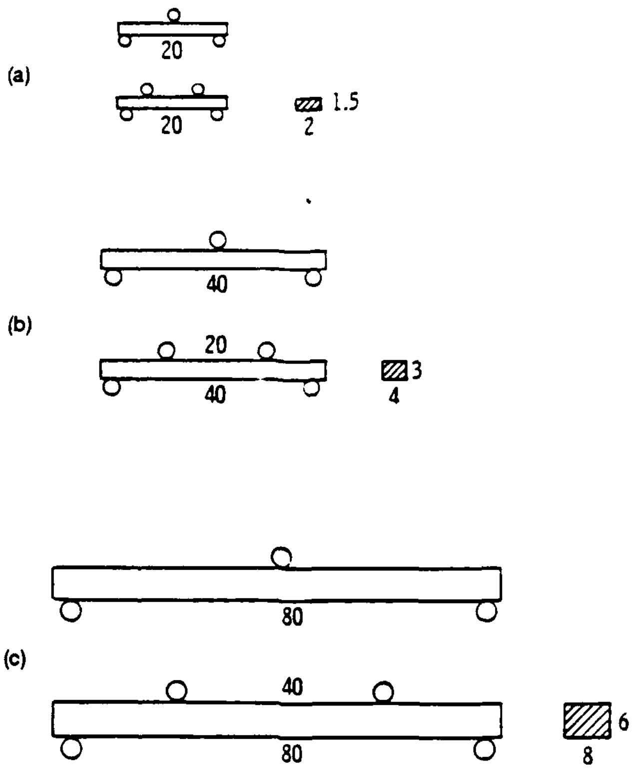


Figure 5. The testing configurations specified in MIL-STD-1942 (MR). Either the 3- or 1/4 4-point modes of loading are permitted. The specimen cross sections are also shown. It is important that the rollers be allowed to rotate or roll. All dimensions are in mm.

this old fixture had substantial error (13% in stress) due to friction from the fixed-load pins, and it was not used thereafter. MTL fabricated extra sets of MIL STD B 4- and 3-point fixtures which were loaned to several laboratories.

NRL used several fixture types in the preliminary phase of the round robin, including fixed-load pins and 20-mm x 40-mm spans. These older fixtures were abandoned when it was determined that they had potential experimental error, particularly load pin friction error. NRL was scheduled to exclusively use MIL-STD-1942 procedures for the main round robin.

IITRI used several schemes including their customary 1/8" x 1/4" specimen tested in 4-point flexure on a fixed-loading pin fixture with 0.875" and 1.750" spans. One alumina sample set was tested with their customary fixture altered to 20-mm x 40-mm spans, but still with fixed-loading pins. This is not MIL-STD-1942 compatible. Finally, a MIL STD B (20-mm x 40-mm spans) fixture was prepared and used to test 3-mm x 4-mm and 3-mm x 6-mm specimens in complete accordance with MIL-STD-1942. Crosshead speeds were, unfortunately, not reported.

ARE used their customary fixture which has 19.05-mm x 40-mm spans in 4-point or 3-point configuration. They also used a MIL STD B fixture on loan from MTL. Specimens were either the 3 mm x 4 mm of MIL STD B, or 4.5 mm x 4.5 mm, which was the customary size. Crosshead speeds were 2.0 mm/min, which is appreciably faster than the 0.5 mm that was specified. It is not clear what interference this may have had with the data.

NPL used their customary fixture which has spans of 20 mm and 40 mm. Loading pins were mounted in needle bearings so as to permit friction relief. The fixture is **virtually in complete accordance with MIL-STD-1942 requirements**. The only significant difference is that the rollers are somewhat larger than the MIL-STD-1942 requirement. (This will only cause a slight increase in error for span change due to contact point tangency shift as the specimens deflect during loading.) Nevertheless, NPL also fabricated an additional MIL-STD-1942 style fixture with 5-mm rollers, rubber bands to hold the rollers against stops (as per an MTL design), and additional articulation such that warped specimens could be accommodated. There should be little difference in results of these two fixtures for well-machined specimens. Only MIL STD B specimens were tested by NPL, either in 3- or 4-point loading. Crosshead rates were 0.5 mm/min.

ORF and MRL obtained fixtures on loan from MTL. Both laboratories tested only in accordance with MIL-STD-1942 procedures.

Lots of 35 specimens for the alumina were delivered, the intent being that 30 specimens were to be tested, and 5 used for spares. All results were to be reported. No data was to be discarded. In practice, some investigators broke 30 and others broke all 35. Lots of 30 RBSN specimens were delivered and all were to be broken.

Humidity, temperature, and loading rate were to be reported. As much fractographic interpretation as possible was encouraged, but not required. Any propensity for failures to occur at loading pins was to be reported.

RESULTS

General

The results of this program are voluminous and are primarily tabulated in the Appendix. A single master data summary is given in Table 5. Table 5 is repeated at the beginning of the Appendix as Table A-1, and all data entries are in the order given in the table. None of the preliminary data samples are included. Table 5 is organized first by the material tested, then the specimen size, the laboratory performing the test, the test method, the results according to the normal (Gaussian) distribution, the results according to a Weibull distribution, and finally, comments. In the latter section, the lot identity (2510 or 2511) is recorded for the RBSN. All data for further interpretation is culled from Table 5. All stresses in this report are in MPa.

A methodical pattern will now be used in order to address the issues raised in Table 2. For each issue, there were a number of experiments that could address the matter at hand. For example, the first issue was: "Using a common procedure, can different laboratories measure flexure strength accurately and precisely?" Common test procedures and materials were used in six instances to answer this question. Six laboratories tested 3-mm x 4-mm alumina specimens according to MIL STD B, 4-point flexure. A comparison of the results in this case will constitute one experiment to answer the issue. Similarly, five laboratories measured the 4-point flexure strength of the RBSN according to MIL STD B. This constitutes another experiment which can be used to answer the same issue.

The confidence bound figures are repeated for convenience, and the variances of this particular example are marked on the graphs.

Table 5

Material	Spec. Size	Laboratory	Method	Normal		Weibull		Comments	Page
				Avg. Str.	Std. Dev	Modulus	Ch. Str.*		
Alumina	1.5 mm x 2 mm	MTL (Quinn)	4 pt (MIL STD A)	372	56	7.3	397		62
Alumina	3 mm x 4 mm	ARE (Godfrey)	3 pt (ARE Fixt.)	452	63	8.0	480		64
Alumina	3 mm x 4 mm	ARE (Godfrey)	3 pt (MIL STD B)	400	25	17.8	412	10 Spec. Only	66
Alumina	3 mm x 4 mm	MTL (Quinn)	3 pt (MIL STD B)	444	51	10.2	466		68
Alumina	3 mm x 4 mm	ORF (Sullivan)	3 pt (MIL STD B)	434	51	10.1	456		70
Alumina	3 mm x 4 mm	ARE (Godfrey)	4 pt (ARE Fixt.)	378	39	11.7	395		72
Alumina	3 mm x 4 mm	IITRI (for AFWAL)	4 pt (MIL STD B)	381	32	14.4	395		74
Alumina	3 mm x 4 mm	MRL (Johnston)	4 pt (MIL STD B)	353	50	7.8	378		76
Alumina	3 mm x 4 mm	ARE (Godfrey)	4 pt (MIL STD B)	323	52	7.3	345		78
Alumina	3 mm x 4 mm	MTL (Quinn)	4 pt (MIL STD B)	364	45	9.3	384		80
Alumina	3 mm x 4 mm	ORF (Sullivan)	4 pt (MIL STD B)	347	44	8.6	367		82
Alumina	3 mm x 4 mm	IITRI (for AFWAL)	4 pt (Mod. IITRI)	365	56	7.3	389		84
Alumina	3 mm x 4 mm	NPL (Morrell)	4 pt (MIL STD B)	359	37	11.6	375		86
Alumina	3 mm x 4 mm	NPL (Morrell)	4 pt (NPL Fixt.)‡	363	39	10.5	381		88
Alumina	3 mm x 6 mm	IITRI (for AFWAL)	4 pt (MIL STD B)	362	33	13.2	376		90
Alumina	3 mm x 6 mm	MTL (Quinn)	4 pt (MIL STD B)	341	48	7.4	363		92
Alumina	3 mm x 6 mm	NPL (Morrell)	4 pt (MIL STD B)	345	34	12.3	360		94
Alumina	1/8" x 1/4"	IITRI (for AFWAL)	4 pt (0.875" x 1.750")	343	49	8.4	363		96
Alumina	6 mm x 8 mm	MTL (Quinn)	4 pt (MIL STD C)	330	35	11.0	345		98
RBSN	3 mm x 4 mm	ARE (Godfrey)	3 pt (ARE Fixt.)	265	24	13.1	276	2511	100
RBSN	3 mm x 4 mm	ARE (Godfrey)	3 pt (MIL STD B)	271	13	24.2	276	2510, 10 Spec.	102
RBSN	3 mm x 4 mm	MTL (Quinn)	3 pt (MIL STD B)	267	13	24.3	273	2510 and 2511	104
RBSN	3 mm x 4 mm	ARE (Godfrey)	4 pt (ARE Fixt.)	263	28	11.1	275	2510	106
RBSN	3 mm x 4 mm	MTL (Quinn)	4 pt (MIL STD B)	237	13	21.7	243	2510 and 2511	108
RBSN	3 mm x 4 mm	IITRI (for AFWAL)	4 pt (MIL STD B)	230	13	20.4	236		110
RBSN	3 mm x 4 mm	ORF (Sullivan)	4 pt (MIL STD B)	234	12	23.6	240	2510 and 2511	112
RBSN	3 mm x 4 mm	ARE (Godfrey)	4 pt (MIL STD B)	274	29	10.4	288	2511	114
RBSN	3 mm x 4 mm	IITRI (for AFWAL)	4 pt (Mod. IITRI)	229	30	8.3	243		116
RBSN	3 mm x 4 mm	NPL (Morrell)	4 pt (MIL STD B)	246	13	22.1	252	2510 and 2511	118
RBSN	3 mm x 4 mm	NPL (Morrell)	4 pt (NPL Fixt.)‡	237	17	16.1	244	2510 and 2511	120
RBSN	4.5 mm x 4.5 mm	ARE (Godfrey)	3 pt (ARE Fixt.)	292	26	12.8	304	2511	122
RBSN	4.5 mm x 4.5 mm	ARE (Godfrey)	3 pt (ARE Fixt.)	278	23	14.5	288	2510	124
RBSN Mach.†	3 mm x 4 mm	MTL (Quinn)	4 pt (MIL STD B)	248	17	17.5	255	2511 Mach.†	126
RBSN Mach.†	3 mm x 4 mm	NPL (Morrell)	4 pt (MIL STD B)	231	22	12.3	241	2511 Mach.†	128

*Characteristic strength of the bend bar
†Surface machined
‡MIL-STD-1942 compatible

Note All strengths in MPa

Key Issues

Issue #1: Using a common procedure, can different laboratories measure flexure strength accurately and precisely?

Experiment #1

Material: alumina
Fixture: 4 point, MIL STD B
Specimen: 3 mm x 4 mm, MIL STD B
Labs: 6

	MTL	IITRI	ARE	NPL	ORF	MRL	All Labs Avg.	All Labs Std. Dev.	All Labs CV
S_{avg}	364	381	323	359	347	353	355		
Std. Dev.	45	32	52	37	44	50			
m	9.3	14.4	7.3	11.6	8.6	7.8	9.8	2.7	0.275
S_{obb}	384	395	345	375	367	376	374	16.9	0.045
							4 Labs		
							9.3	1.6	0.176
							376	6.9	0.018

Comments/Conclusion

All of the individual Weibull graphs are "well behaved" and not unduly influenced by outlier or stray specimen strengths.

The variability of m from lab to lab has a CV of 0.275. This is too high compared to a predicted value of 0.18 for samples of 30 specimens. (Figure 2a is also shown here as Figure 6a.) The IITRI data set has the most extreme Weibull modulus and, if it is deleted, the mean m is 9.2 and the CV is 0.20. This CV is consistent with the expected scatter. Figure 3a is now consulted to consider how extreme the IITRI results are. The m_{est} / m_{true} is 14.4/9.2 = 1.57. This is well beyond the 99th percentile for 30 specimens. In fewer than 1 out of 100 occasions would an m value of this deviation occur. This is illustrated in Figure 7a.

The CV of the characteristic strength for all sets is also too high (0.045) compared to the expected inherent variability (0.025) from Figure 2b (illustrated in Figure 6b) for an m of 9.2. In this instance, the ARE S_{obb} seems too low. If only the ARE lot is deleted, the mean S_{obb} is 379 and the CV is 0.028, which is much more consistent with the expected 0.025. Consulting Figure 3b regarding the ARE outcome (as shown in Figure 7b), the S_{obb} / S_{true} of 345/379 = 0.91 is very atypical (off the graph) and will occur much less than 1% of the time. The IITRI S_{obb} appears to be atypically high as well; 395/374 = 1.056, which is well beyond the 99th percentile. With both the IITRI and ARE S_{obb} deleted, CV = 0.018, which is in better agreement with Figure 2b (illustrated in Figure 6b).

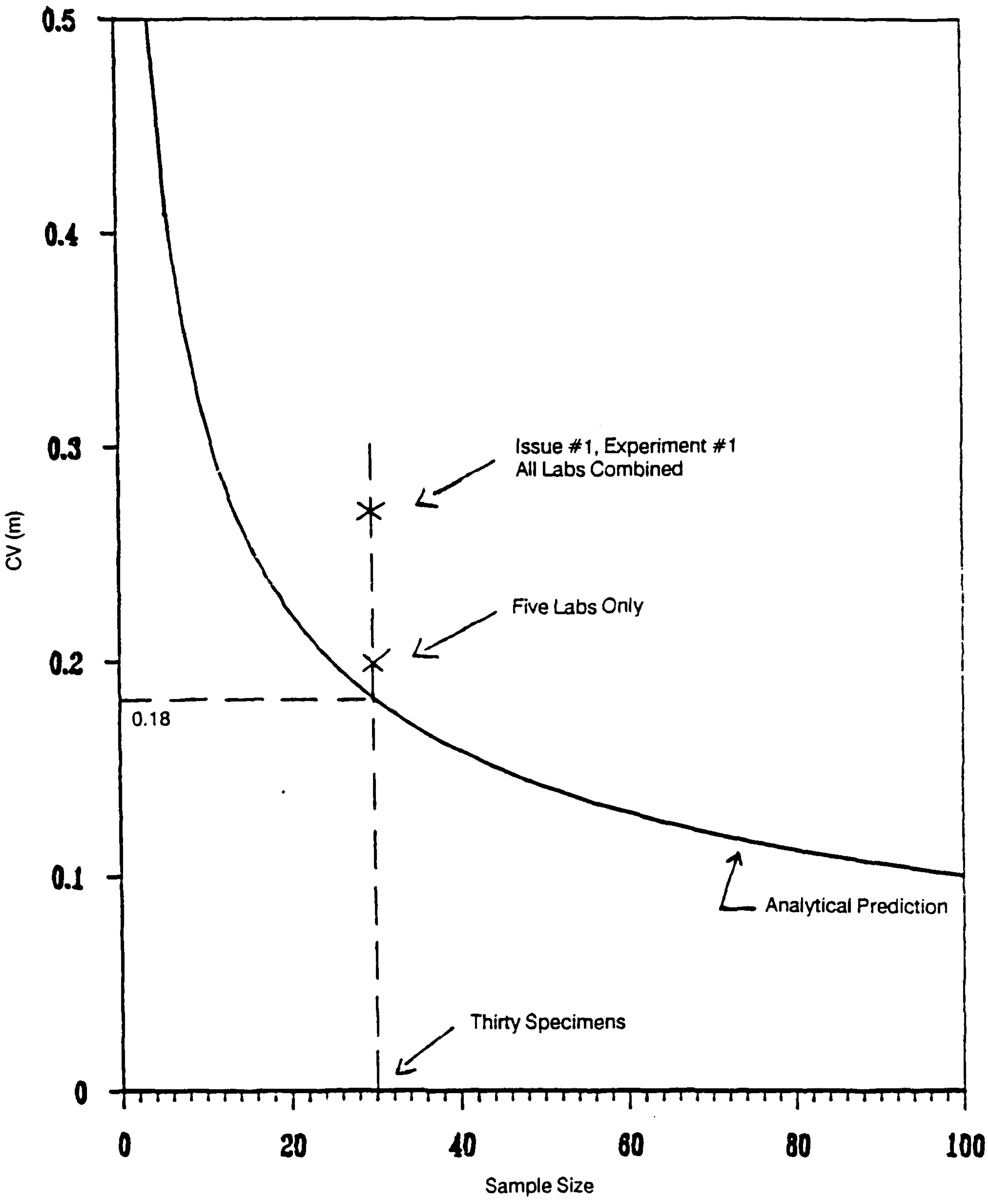


Figure 6a. CV of m as a function of sample size. For a sample size of 30 specimens, a CV of 0.18 is predicted.

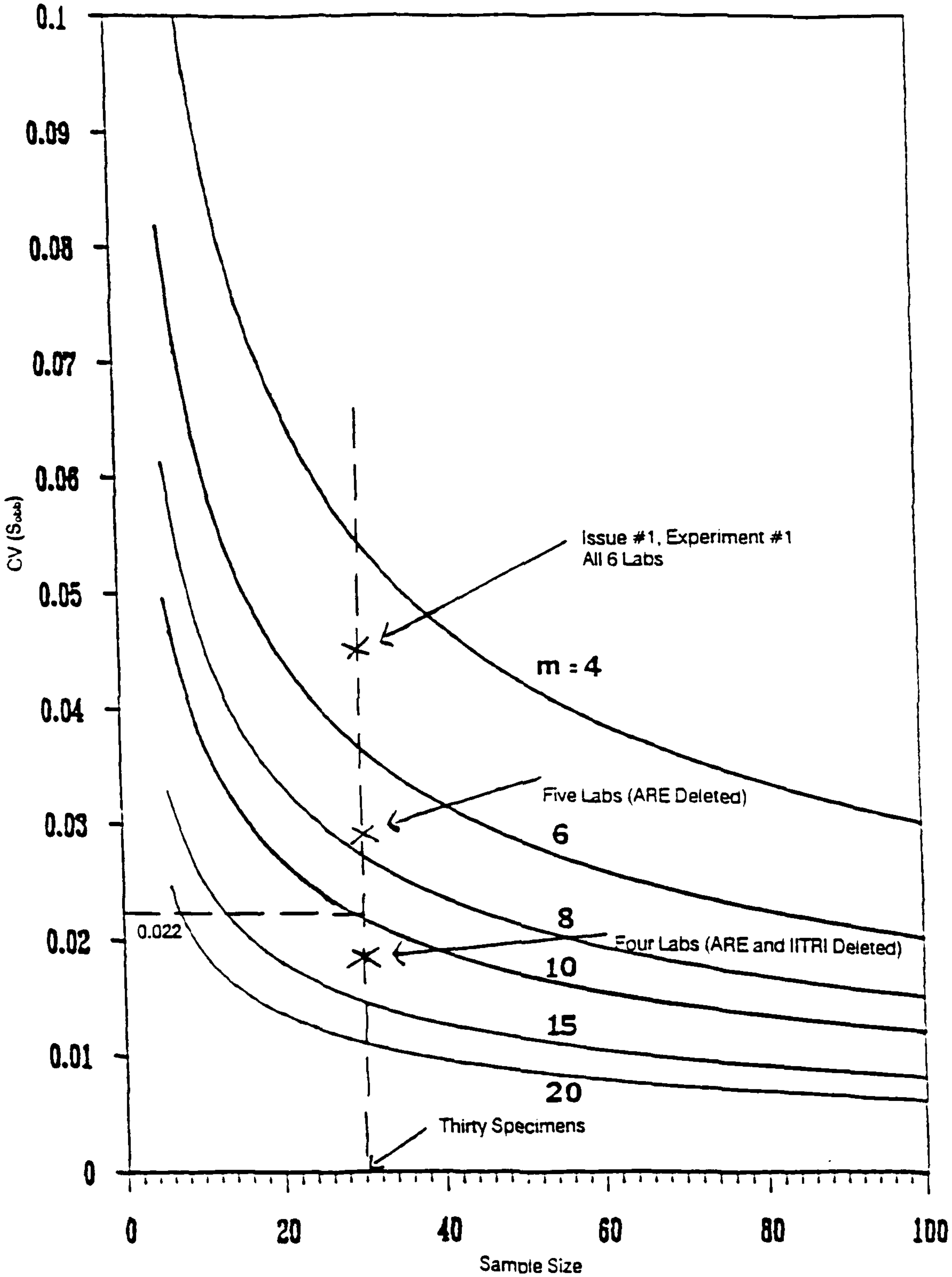


Figure 6b. CV for S_{obb} as a function of sample size. For a sample size of 30 specimens, a CV of 0.025 is predicted for m = 9.2; a CV of 0.022 is predicted for m = 10

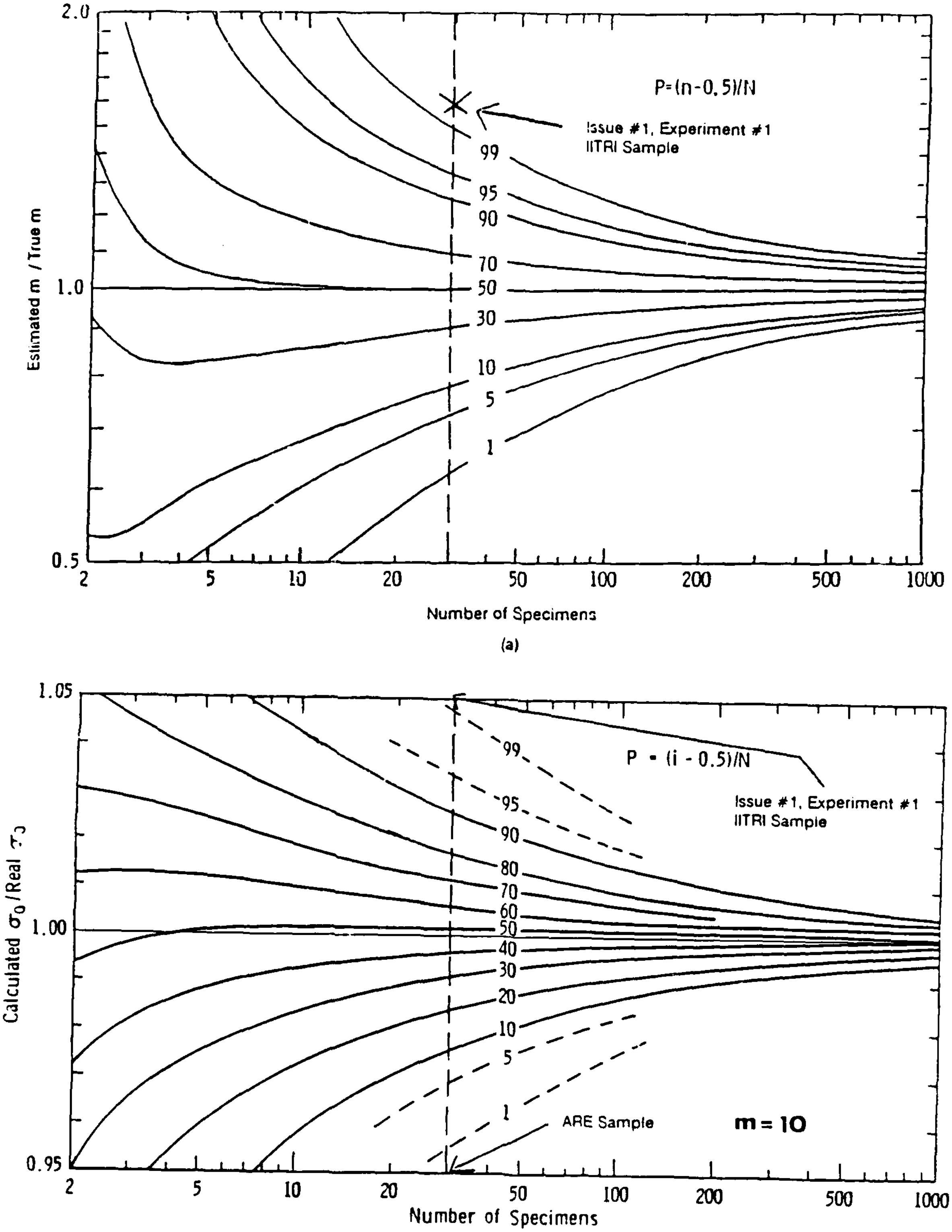


Figure 7. The confidence intervals for Weibull modulus m, and the characteristic strength of the bend bar, S_{obb}. The estimated parameters are derived from a single sample. The confidence bounds for m are shown in (a), and the bounds for S_{obb} are in (b). The latter were derived for an m of 10. From Reference 6.

It is thus concluded that at least four of the six labs got consistent results in this instance. The IITRI set was atypical in having too high an m. This is unusual since experimental errors generally create higher scatter (a lower m). The S_{obb} of the IITRI data may be atypically high as well. The ARE data has an acceptable modulus (m), however, the S_{obb} is too low.

Experiment #2

Material: alumina
Fixture: 3 point, MIL STD B
Specimen: 3 mm x 4 mm, MIL STD B
Labs: 3

	MTL	ARE	ORF	All Labs Avg.	All Labs Std. Dev.	All Labs CV
S_{avg}	444	400	434	426		
Std. Dev.	51	25	51			
m	10.2	17.8	10.1	12.7	4.4	0.35
S_{obb}	466	412 (Only 10 Spec.)	456	445	29	0.065

Comments/Conclusion

Only three labs participated in this exercise and, thus, taking a standard deviation is speculative. The Weibull graphs were "well behaved" in each case, however.

The CV of m is too high (0.35) compared to the expected 0.18. The ARE m value is atypically high (indeed, is the highest value of any data set for the alumina), but it was based on **only 10 specimens**. The other two lab results are very consistent and average 10.2, which is close to the value obtained in 4-point testing. The ARE outcome, m_{est} / m_{true} = 17.8/10.2 = 1.76. Consulting Figure 3a for 10 specimens, this could occur at the 96% interval. Four times out of 100 could the modulus be measured this high or, alternatively, 8% of the outcomes could vary this much from the mean.

The S_{obb} variability (0.065) is too high for sample sizes of 30 and, once again, it is the ARE lot which is the most extreme, with a S_{obb} of 412. The othe. · bs had very consistent S_{obb} (avg. = 461). Again, it should be considered that the ARL lot was only 10 specimens, and consulting Figure 3b, for a S_{obb} / S_{true} of 412/461 = 0.89, it appears that the ARE S_{obb} is atypically low (even for a sample size of 10).

It is obviously speculative to make conclusions based upon so few data sets, but it appears that two labs obtained consistent results. ARE tested only 10 specimens, and the m value obtained is rather high, but is possible; however, the S_{obb} is atypically low.

Experiment #3

Material:	alumina
Fixture:	4 point, MIL STD B
Specimen:	3 mm x 6 mm, MIL STD B
Labs:	3

				All Labs		
	MTL	IITRI	NPL	Avg.	Std. Dev.	CV
S_{avg}	341	362	345	349		
Std. Dev.	48	33	34			
m	7.4 (10.5)	13.2	12.3	10.9	3.1	0.285
S_{obb}	363	376	360	336	8.5	0.023
					Revised	
m				12.0	1.4	0.115
S_{obb}				366	8.5	0.023

Comments/Conclusion

Only three labs participated in this exercise, and taking a standard deviation is speculative. The Weibull graphs of the IITRI and NPL sample lots were "well behaved." The MTL graph was strongly influenced by one unusually low strength specimen (see the Appendix for details).

Once again, the CV for m is too high (0.285) relative to the inherent scatter (0.18) of Figure 2a. The MTL data lot apparently has too low an m. The MTL data was reexamined and the single low strength specimen was unduly influential. Optical and scanning electron microscope (SEM) fractography revealed that the defect was a huge (0.5 mm) red and black inclusion with large grains nearby. Such a defect was extremely unusual and not seen in any other specimen in any sample. Thus, for the purposes of this exercise, the datum can be deleted.

With the point deleted, the MTL m and S_{obb} are 10.5 and 363. The CV of all three data samples becomes 0.115 for m, and 0.023 for S_{obb}. Both variances are quite typical and reasonable, as shown in Figures 2a and 2b.

Thus, the answer in this instance is that the labs did get completely consistent results.

Experiment #4

Material: RBSN
Fixture: 4 point, MIL STD B
Specimen: 3 mm x 4 mm, MIL STD B
Labs: 5

	MTL	IITRI	ARE	NPL	ORF	All Labs Avg.	All Labs Std. Dev.	All Labs CV
S_{avg}	237	230	274	246	234			
Std. Dev.	13	13	29	13	12			
m	21.7	20.4	(10.4) 18.7	22.1	23.6	21.3	1.8	0.087
S_{obb}	243	236	(288) 277	252	240	250	16.4	0.066

Comments/Conclusion

The ARE Weibull graph is not well behaved. There is some curvature at the high strength end, and one unusually high strength specimen had an undue influence upon the graph (see Appendix). If this data is deleted, then the Weibull parameters 18.7 MPa and 277 MPa are in better agreement with the other results, and the graph is better behaved.

The scatter in the m values is unusually low (0.087 CV) for a sample size of 30 (0.18 predicted in Figure 2a). This is one instance where the results are extremely consistent, more so than the inherent statistical scatter would predict. It is not too surprising that this event would occur at least once in the round robin exercise. Consideration of all other results suggests that the Weibull modulus for the RBSN is approximately 20.

The scatter in the S_{obb} is unacceptably high, however; 0.066 compared to a predicted 0.012 for m = 20, and a sample size of 30 specimens (Figure 2b). The outlier here may be the ARE sample, and if it is deleted, the CV becomes only 0.028, however, this is still too high. Going one step further, if the next most deviant group, the NPL sample, is deleted, then the CV decreases to only 0.015, which is more consistent with the expected scatter. (This seems contrary to intuitions, since the NPL result (252 MPa) is quite close to the others.) The point here is that Figure 2 indicates that for a very high m, results for S_{obb} should be extremely consistent, but this does not seem to be experimentally confirmed.

The answer to the issue appears to be that m values can be consistently measured, however, the S_{obb} values less so.

Experiment #5

Material: RBSN
Fixture: 3 point, MIL STD B
Specimen: 3 mm x 4 mm, MIL STD B
Labs: 2

	MTL	ARE	All Labs Avg.	Std. Dev.	CV
S_{avg}	267	271			
Std. Dev.	13	13			
m	24.3	24.2	24.2		
S_{obb}	273	276 (10 Spec. Only)	275		

Comments/Conclusion

The results, in this instance, are extraordinarily consistent. The analysis is unnecessary since the agreement is exceptional. The answer is yes in this instance.

Experiment #6

Material: RBSN, with the surface-reaction layer machined off, lot 2511 only
Fixture: 4 point, MIL STD B
Specimen: 3 mm x 4 mm, MIL STD B
Labs: 2

	MTL	NPL	All Labs Avg.	Std. Dev.	CV
S_{avg}	248	231			
Std. Dev.	17	22			
m	17.5	12.3	14.9		
S_{obb}	255	241	248		

Comments/Conclusion

With only two participating laboratories, it is not appropriate to compute a standard deviation or the coefficient of variation; therefore, a direct comparison of the results through Figures 3a and 3b is appropriate. Both sample lots had well behaved Weibull graphs.

For the Weibull modulus, assume the average value 14.9 is the true m. (The effect of machining off the reaction layer seems to reduce the Weibull modulus from approximately 20.) The two ratios for Figure 3a are then 17.5/14.9 = 1.17 and 12.3/14.9 = 0.83. This variability is quite reasonable and typical for sample sizes of 30, as shown in Figure 3a.

Figure 3b was prepared for an m of 10, but can be used for guidance. The average S_{obb} is 248 and the S_{obb} / S_{true} ratios are 1.028 and 0.972. This variability corresponds to 7% and

91% confidence intervals, or is possible 16% of the time (7% + 9%) if m were 10. For an m of 14.9, it is less plausible due to the tighter confidence bounds expected for higher m values. No clear conclusion can be made in this instance.

Of course, there is every reason to expect that there could be a variation, since the surface machining was done by different machine shops, and probably by different methods, and to different depths.

Issue #2: Does the 3-mm x 6-mm specimen give satisfactory results relative to the 3-mm x 4-mm configuration? The Weibull volume analysis predicts 4.2% strength difference.

Experiment #1

Material: alumina
Fixture: 4 point, MIL STD B
Labs: 3

	MTL		IITRI		NPL	
	3 mm x 4 mm	3 mm x 6 mm	3 mm x 4 mm	3 mm x 6 mm	3 mm x 4 mm	3 mm x 6 mm
S_{avg}	364	341	381	362	359	345
Std. Dev.	45	48	32	33	37	34
m	9.3	7.4 (10.5)	14.4	13.2	11.6	12.3
S_{obb}	384	363	395	376	375	360
Strength Difference	5.8%		5.1%		4.2%	
Overall Difference			5.0%			

Comments/Conclusion

The larger 3-mm x 6-mm specimen did have a lower strength on the average than the 3-mm x 4-mm specimen. The difference is very close to the prediction (4.2%) based upon effective specimen volume for a Weibull modulus of 9.8, which is the average of the 3-mm x 4-mm data. Fractography confirmed that the strength-limiting flaws are volume distributed.

(Issue #1, Experiment #3, already confirmed that the 3-mm x 6-mm data samples were consistent with each other.)

The answer to the issue is, thus, yes.

Issue #3: Given a constant specimen size (3 mm x 4 mm), are "old" or "current" test fixtures giving results consistent with MIL-STD-1942 fixtures?

Experiment #1

Laboratory: MTL
Material: alumina (preliminary lot)
Old Method: 4 point, 1.6" x 0.8" spans, fixed-load points

		Quinn	Goulet	Harvey	MIL-STD-1942		
	Old/Current (10 Spec. Only)	MIL-STD-1942	MIL-STD-1942	MIL-STD-1942	Avg.	Std. Dev.	CV
S_{avg}	401	375	372	381			
Std. Dev.	44	34	43	43			
m	9.7	13.4	10.3	10.5	11.4	1.7	0.152
S_{obb}	421	391	391	400	394	5.2	0.013

Comments/Conclusion

This data was from the preliminary round robin work, and is shown in Figure 4. (It is not listed in Table 5.) The "old" AMMRC (MTL) fixture was determined to be erroneous due to fixed-load points which cause friction error. This was corroborated by experiments on other materials as well.

Please note that in contrast, three different MTL operators, on *three different machines*, with three different fixtures, on three different days, got consistent results with the MIL-STD-1942 procedure. (This is a test of ruggedness.) The CV of both m and S_{obb} for the three MIL-STD-1942 samples are well within the typical inherent scatter curves of Figures 2a and 2b.

Experiment #2

Laboratory: NRL
Material: alumina (preliminary lot)
Method: 4 point, 40-mm x 20-mm spans, fixed-load pins

	Old/Current (15 Spec. Only)	MIL-STD-1942
S_{avg}	401	381
Std. Dev.	41	47
m	11.0	9.5
S_{obb}	421	401

Comments/Conclusion

The old NRL fixture was erroneous due to fixed-load pins which caused friction error. This was corroborated by NRL with tests on other materials as well. Please note that this conclusion is identical to the MTL experience cited immediately above.

Experiment #3

Laboratory: IITRI
Material: alumina
Method: 4 point, current, 1.75" x 0.875" spans modified to 40 mm x 20 mm, fixed-load pins

	Old/Current	IITRI MIL-STD-1942	All 6 Samples MIL STD B*
S_{avg}	365	381	
Std. Dev.	56	32	
m	7.3	14.4	9.8
S_{obb}	389	395	374

Comments/Conclusion

A direct comparison of the IITRI results to each other indicates S_{obb} is consistent, but the m values are not very consistent.

The 3-mm x 4-mm MIL-STD-1942 test results have been previously discussed in Issue #1, Experiment #1. Both m and S_{obb} of the IITRI results seemed atypical.

The 3-mm x 4-mm results on the old/current IITRI fixture may possibly have been affected by five low strength specimens which caused an m somewhat less than the typical value of 10 for the sintered alumina. The ratio 7.3/9.8 = 0.75 is not unreasonable, however, as shown in Figure 3a. A modulus as low as this could occur 7% of the time. The variance of S_{obb}, 389/374 = 1.040 is at the 98% confidence band, however (Figure 3b), and probably is atypical.

Thus, there seems to be a problem of consistency in this instance.

Experiment #4

Laboratory: ARE
Material: alumina
Method: 4 point, current, 40-mm x 19-mm spans, fixed-load pins

	Old/Current	ARE MIL-STD-1942	All Labs MIL-STD-1942
S_{avg}	378	323	
Std. Dev.	39	52	
m	11.7	7.3	9.8
S_{obb}	395	345	374

Comments/Conclusion

The ARE current data set has a well behaved Weibull graph. If the S_{obb} for either the current or the MIL-STD-1942 data sets is considered correct, then the alternative set is atypical. (m_{est} / m_{true} = 395/345 = 1.145, or = 345/395 = 0.873, see Figure 3b). The S_{obb} of the ARE MIL-STD-1942 lot has been previously characterized as too low, however (see Issue #1, Experiment #1).

The ARE current lot can be compared to the average MIL-STD-1942 results from Issue #1, Experiment #1 (m = 9.8 and S_{obb} = 374). The ARE current results then give an m_{est} / m_{true} ratio of 11.7/9.8 = 1.19, which is quite reasonable, as shown in Figure 3a. The S_{obb} / S_{true} ratio is 395/374 = 1.056, which is atypically high once again (Figure 3b).

It is, therefore, concluded that for the ARE current practice, the Weibull modulus is quite consistent, however, the S_{obb} is atypically high.

Experiment #5

Laboratory: ARE
Material: alumina
Method: 3 point, current, 40-mm span, fixed-load pins

	Old/Current	ARE MIL-STD-1942	ORF + MTL MIL-STD-1942
S_{avg}	452	400	
Std. Dev.	63	25	
m	8.0	17.8	10.1
S_{obb}	480	412 (10 Spec. Only)	461

Conclusion

The current fixture results are not consistent with the ARE-performed MIL-STD-1942 results, both the Weibull modulus and the S_{obb} being well outside reasonable confidence limits of Figures 3a and 3b. This is considering the data sets with respect to each other.

The ARE MIL-STD-1942 3-point results have been previously discussed in Issue #1, Experiment #2, where it was determined that the modulus was rather high, but possible, but the S_{obb} was atypically low. These observations were tempered by the fact that only 10 specimens were tested.

The current 3-point fixture results, on the other hand, give results in somewhat better agreement with the other 3-point alumina results by MTL and ORF (see Issue #1, Experiment #2). If the Weibull modulus is 10 for the alumina, then the current ARE m value: 8.0/10.0 = 0.8, is very plausible for 30 specimens (Figure 3a). Comparing the S_{obb} to the average of the ORF and MTL results in 480/461 = 1.041, which is a deviation at the 98% confidence limit (Figure 3b) and is not very consistent.

In summary, the Weibull modulus of the ARE current fixture sampling is consistent with other labs' 3-point results, but the S_{obb} seems too high. The ARE-conducted 3-point MIL-STD-1942 results are not consistent with the current fixture results, however, only 10 specimens were tested.

Experiment #6

Laboratory: NPL
Material: alumina
Method: 4 point, current, 40-mm x 20-mm spans, rolling and articulating

	Old/Current	NPL MIL-STD-1942
S_{avg}	363	359
Std. Dev.	39	37
m	10.5	11.6
S_{obb}	381	375

Conclusion

Virtually identical results are obtained since current fixtures are virtually MIL-STD-1942 compatible. This confirms that the exact details of the fixture **do not matter**. The answer to the issue is yes in this instance.

Experiment #7

Laboratory: IITRI
Material: RBSN
Method: 4 point, current, 1.75" x 0.875" spans modified to 40 mm x 20 mm, fixed-loading pins

	Old/Current	IITRI MIL-STD-1942
S_{avg}	229	230
Std. Dev.	30	13
m	8.3	20.4
S_{obb}	243	236

Comments/Conclusion

The IITRI MIL-STD-1942 results here are well behaved and have good agreement with the other MIL-STD-1942 samples (Issue #1, Experiment #4).

The current fixture sample has pronounced curvature on the Weibull graph, however, which cannot be traced to one or a few points (see the Appendix). The Weibull modulus is unusually low, indeed, the lowest of all the RBSN samples. If the true modulus is 20 (Issue #1, Experiments #4 and #5), then m_{est} / m_{true} = 8.3/20 = 0.415 which is way below even the 1% confidence limit of Figure 3a.

The S_{obb} is quite consistent with the IITRI 4-point MIL-STD-1942 results (236 MPa), and with the average of all the 4-point MIL-STD-1942 results (252 MPa from Issue #1, Experiment #4).

In this instance, the m is not consistent, but the S_{obb} is.

Experiment #8

Laboratory: NPL
Material: RBSN
Method: 4 point, current, 40-mm x 20-mm spans, rolling and articulating

	Old/Current	NPL MIL-STD-1942
S_{avg}	237	246
Std. Dev.	17	13
m	16.1	22.1
S_{obb}	244	252

Comments/Conclusion

This experiment gave the same conclusion as Experiment #5 in this set. The current fixture type is virtually compatible with MIL-STD-1942 and does give consistent results.

Experiment #9:

Laboratory: ARE
Material: RBSN
Method: Current, 40-mm span, 3 point

	Old/Current	ARE MIL-STD-1942
S_{avg}	265	271
Std. Dev.	24	13
m	13.1	24.2
S_{obb}	276	276 (10 Spec. Only)

Comments/Conclusion

Both the current fixture results and the MIL-STD-1942 results are well behaved on the Weibull graphs. The S_{obb} values are identical.

One the other hand, the Weibull moduli are very different. If the true modulus is 20 (see Issue #1, Experiment #4), then $m_{est} / m_{true} = 13.1/20 = 0.65$, which is at the 3% confidence interval of Figure 3a. The slope of 24.2 is quite consistent relative to a true value of 20, for a sample size of only 10.

In this instance, it appears that the S_{obb} is consistent, however, the Weibull modulus is not.

Experiment #10

Laboratory: ARE
Material: RBSN
Method: current, 4 point, 40-mm x 19-mm spans

	Old/Current	ARE MIL-STD-1942
S_{avg}	263	274
Std. Dev.	28	29
m	11.1	10.4 (18.7)
S_{obb}	276 (Lot 2510)	288 (277) (Lot 2511)

Comments/Conclusion

Both of these data samples are unusual in that there is a definite curvature at the high end of the Weibull graph. Three to five points on each graph contribute to this curvature, which is very similar on the two sets. The curvature was not observed in any other data set, however. Because of the curvature, the standard analysis was not used.

The results are reasonably consistent to each other in this instance, except that there is a uniform shift of about 4.2% of one curve relative to the other (274/263 = 1.042, with the MIL-STD-1942 procedure giving the higher results). If Figure 3b is consulted for guidance, a 4% location parameter difference (S_{obb} or S_{avg}) is not likely (98% confidence interval) for an m of 10. It is less likely if the m is 20 (which is typical of most of the other data samples, and for the present two ARE samples if the upper strength points are deleted).

The MIL-STD-1942 set has been previously compared to other MIL-STD-1942 results (Issue #1, Experiment #4). The modulus was consistent if one data was deleted (data in parentheses above), but the S_{obb} was not in agreement.

Please note that specimens were from two different lots in this instance, which may contribute to the difference in results.

Issue #4: Are "old" or "current" practices giving results comparable to MIL-STD-1942 (MR) size B?

Experiment #1

Laboratory: IITRI/AFWAL
Material: alumina
Test Method: old, 4 point, 1.75" x 0.875" spans
Specimen: 1/8" x 1/4" cross-section size

	Old/Current	IITRI 3 mm x 4 mm MIL-STD-1942	IITRI 3 mm x 6 mm MIL-STD-1942	Avg. 3 mm x 4 mm MIL-STD-1942
S_{avg}	343	381	362	
Std. Dev.	49	32	33	
m	8.4	14.4	13.2	9.8
S_{obb}	363	395	376	374

Comments/Conclusion

The IITRI old procedure results are reasonably well behaved on the Weibull graph, although there is a little curvature at the low strength end.

The old/current results will be compared to the ITTRI-generated 3 mm x 6 mm, 4-point sample, and to the average 3-mm x 4-mm results of the other labs. The IITRI 3-mm x 4-mm results seem to be atypical, as discussed in Issue #1, Experiment #1.

The Weibull modulus of the old procedure sample, 8.4, is consistent with m values of 9 to 12 that were previously determined in 3-mm x 4-mm testing (both 3 and 4 point), and with 3-mm x 6-mm results (see Issue #1, Experiments #1, #2, and #3).

The S_{obb} must be compared in the context of expected variations due to different volume specimens. The effective volume of a 1/4 point, 4-point flexure specimen is:

$$V_E = V\,(m + 2)/4\,(m + 1)^2$$

which for an m of 10:

$$V_E = 0.025\ V$$

where V is the volume of the specimen between the outer loading points.

For the 40-mm span, MIL-STD-1942 configuration B with 3-mm x 4-mm specimen:

$$V_{E},\ 3\ \text{mm} \times 4\ \text{mm} = 0.025\ (3\ \text{mm} \times 4\ \text{mm} \times 40\ \text{mm}) = 11.9\ \text{mm}^3.$$

For the 40-mm span, MIL-STD-1942 configuration B with 3-mm x 6-mm specimen:

$$V_{E},\ 3\ \text{mm} \times 6\ \text{mm} = 0.025\ (3\ \text{mm} \times 6\ \text{mm} \times 40\ \text{mm}) = 18.0\ \text{mm}^3.$$

And for the IITRI 1.875" span with 1/8" x 1/4" specimen:

$$V_{E},\ 1/8'' \times 1/4'' = 0.025\ (3.18\ \text{mm} \times 6.35\ \text{mm} \times 45.3\ \text{mm}) = 22.7\ \text{mm}^3.$$

These effective volumes predict a volume effect upon strength such that the 3 mm x 4 mm MIL-STD-1942 configuration should be 6.7% stronger than the old IITRI procedure, and the 3 mm x 6 mm MIL-STD-1942 configuration should be 4.2% stronger than the old IITRI procedure.

The S_{obb} of the old IITRI procedure relative to the average of the other laboratories 3-mm x 4-mm results (Issue #1, Experiment #1) is:

374/363 = 1.030

which is less than the 1.067 predicted. The old IITRI procedure should have given 351 MPa to be in perfect accord here. The ratio of 363/351 is 1.034, which is a variation at the 93% confidence interval from Figure 3b. This variation on the high side could, thus, occur 7% of the time.

The S_{obb} of the old IITRI procedure relative to the IITRI 3-mm x 6-mm results is:

376/363 = 1.036

which is in good agreement with the prediction.

In conclusion, the old/current procedure at IITRI gave a Weibull modulus that was consistent with other results. The S_{obb} was consistent with the IITRI 3-mm x 6-mm results, but unclear with respect to other lab 3-mm x 4-mm results.

Experiment #2

Laboratory: ARE
Material: RBSN, note two data sets, one exclusively lot 2510, and the other 2511
Method: 3 point, current, 40-mm span, fixed-load pins
Specimen: 0.18" x 0.18" cross section

	Current	Current	ARE, 3 Point, 3 mm x 4 mm, MIL-STD-1942	ARE, 3 point, 3 mm x 4 mm Current
S_{avg}	278	292	271	265
Std. Dev.	23	26	13	24
m	14.5	12.8	24.2	13.1
S_{obb}	288 (Lot 2510)	304 (Lot 2511)	276 (Lot 2510) (10 Spec. Only)	276

Comments/Conclusion

Specimens for the two samples were taken exclusively from lots 2510 or 2511. ARE presumably deliberately did this to compare strengths from the two nitridation runs to verify their consistency. These 0.18" x 0.18" (4.5-mm x 4.5-mm) specimens were made from a different green billet than the two used for all the other RBSN specimens.

The Weibull graphs in each of the cases here were well behaved. The current ARE sample Weibull graphs are very similar, but the 2511 lot is shifted to higher strengths by 1.050, or 5%.

The Weibull moduli of the two 0.18" lots are very consistent, but are very different than the values of about 20 that were typical for most 3-mm x 4-mm specimens. The moduli are also very different than the ARE MIL-STD-1942-generated 3-point data listed above (although there were only 10 specimens). Figure 3a shows that for a sample size of 30, a modulus of 12.8 would occur at about the 3% confidence limit for a true m of 20; the modulus of 14.8 would be at the 10% interval.

The 0.18" x 0.18" specimens have higher S_{obb} values than the 3-mm x 4-mm specimens, which is the opposite of what one would expect from a Weibull size effect.

The 0.18" x 0.18" sample moduli are in better agreement with the ARE 3 mm x 4 mm, current fixture results. The S_{obb} results, again, are the opposite of expected; the larger specimens being stronger.

A definitive interpretation is difficult to reach here because of the interfering effect of the different green billets, which may have an effect in this instance. The Weibull moduli of the 0.18" x 0.18" cross-section specimens may be inherently different than for the 3-mm x 4-mm samples.

Secondary Issues

Issue #5: Does a Weibull size analysis apply to the strength da.a?

A sufficiently diverse set of sizes was available for the alumina, and fractography revealed that nearly all flaws were volume distributed. The strengths from two sizes can be related through their "effective volumes," V_E:

for 1/4 to 4 point: $V_E = V(m + 2) / 4(m + 1)^2$

for 3 point: $V_E = V / 2(m + 1)^2$

where V is the specimen volume between the outer fixture loading pins.

The effective volumes for the alumina specimens of this study are given in Table 6 along with the strength data. Only MTL data was used in the present analysis.

Table 6. EFFECTIVE VOLUMES AND STRENGTHS FOR ALUMINA SPECIMENS

	V	V_E	S_{obb}	m
Four Point				
A 1.5 mm x 2 mm x 20 mm	60 mm^3	1.49 mm^3	397 MPa	7.3
B 3 mm x 4 mm x 40 mm	480 mm^3	11.90 mm3	384 MPa	9.3
B* 3 mm x 6 mm x 40 mm	720 mm^3	17.9 mm3	363 MPa	10.5
C 6 mm x 8 mm x 80 mm	3840 mm^3	95.2 mm3	345 MPa	11.0
Three Point				
B 3 mm x 4 mm x 40 mm	480 mm^3	1.98 mm3	466 MPa	10.2

The strength of different sized specimens should be related as follows:

$$\frac{S_{obb,\ A}}{S_{obb,\ B}} = \left(\frac{V_{E,\ B}}{V_{E,\ A}}\right)^{1/m}$$

A graph of S_{obb} versus V_E should, therefore, have a slope of -1/m. Figure 8 shows such a graph with a line of slope 1/10 fitted to the specimen size B or B* (3-mm x 6-mm) data. The agreement is excellent for such specimens, but the smaller A size, and larger C size, deviate significantly. The A specimen data is 15% less than the line, and the C data is 7.2% higher. Both deviations are too high to be typical statistical fluctuations (Figure 3b).

An underlying assumption to such simple analysis is that the flaw populations are identical in the specimens. The strength level is different for the various sizes merely due to the greater odds of finding a larger flaw in the larger specimen. It is assumed that the specimens are all from consistent batches of material, that specimens taken from one billet have the same type flaws as other specimens from other billets.

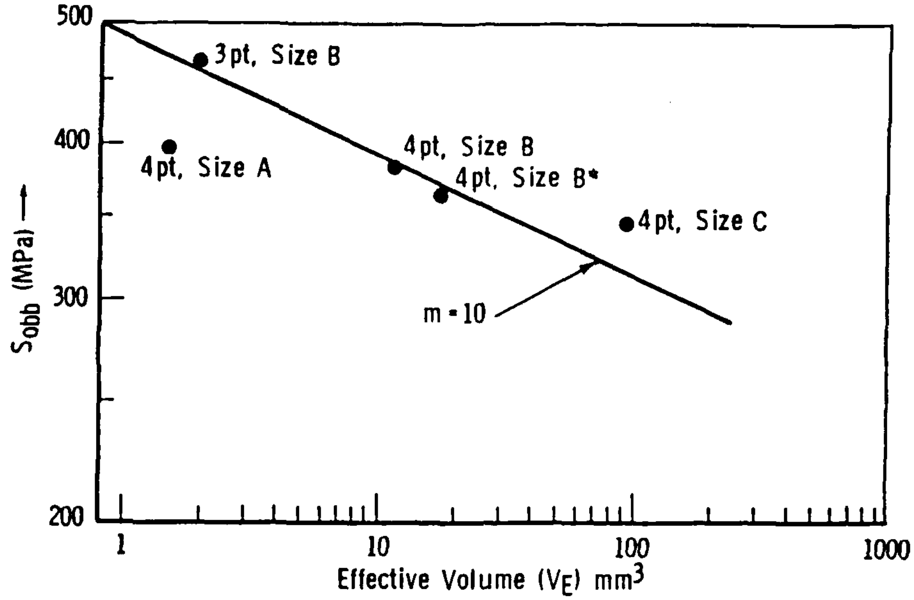


Figure 8. Sobb as a function of effective volume for alumina specimens. All data is from MTL testing. The individual points are for samples of 30 specimens, and are labelled by the test method, then specimen size.

A further restriction occurs if more than one flaw type is present. For any one specimen type this is not a problem, but for different sized specimens comparisons are more difficult, since the likelihood of one flaw type causing failure may scale differently with size (especially if the Weibull moduli are different). If multiple flaw populations are present, then simple strength scaling relationships, as given above, will not be adequate. References 3, 6, and 13 cover these issues in more detail.

Fractography did reveal that more than one flaw population was present. Thus, it is not surprising that the A and C specimens did not give the expected volume dependence. The B or B* specimens did reflect the proper strength-volume scaling since the specimens had similar mixtures of flaws.

Fractography also revealed that the C specimens failed a high fraction of the time (17/30) from power agglomerates. This type of flaw occurred in the other specimen types, but not as frequently. This suggests that the C specimens came from one billet, or a portion of a billet, that had a higher concentration of such defects than the other billets. Presumably, the B specimens from such a billet were randomly distributed in all data sets by the process of riffling. Ideally, all specimens would be randomly selected from random portions of randomly selected billets. Practicality determined that the C specimens were all cut from one billet. A more cautious approach would have been to machine a few C specimens out of each billet. These precautions are appropriate if a billet-to-billet variability is expected. All evidence at the beginning of this exercise indicated that the billets were consistent, and the precautions were regrettably not taken. Reference 10 further describes billet-to-billet consistency issues for the sintered alumina.

13. SERVICE, T., RITTER, J. JR., and SONDERMAN, D. *Bimodal Strength Populations.* Am. Ceram. Soc. Bull., v. 64, no. 9, 1985, p. 1276-1280.

Issue #6: Does machining the reaction layer off of the RBSN alter the strength?

Two laboratories, MTL and NPL, participated in this exercise, wherein a sample of 30 specimens had the surface-reaction layer removed by machining. Strengths were measured in 4-point bending according to MIL-STD-1942. Results were compared to as-fired specimen results, which were also tested by the MIL-STD-1942 procedure. Both samples were exclusively lot 2511 specimens, however. Only a small amount of material was machined off of the MTL specimens, but the actual amount was not recorded. The strength results are given in Table 7.

Table 7. AS-FIRED VERSUS MACHINED RBSN STRENGTHS

	NPL		MTL	
	As-Fired	Machined	As-Fired	Machined
m	22.1	12.3	21.7	17.5
S_{obb}	252	241	243	255

The **machined** specimen results have previously been compared to each other (Issue #1, Experiment #6). The Weibull graphs were well behaved. The Weibull moduli are consistent (although the NPL value was low compared to most other results). It was not clear whether the S_{obb} results were consistent.

The **as-fired** results have been discussed previously as well (Issue #1, Experiment #4). The m values were consistent, but the NPL S_{obb} result was a little high.

Table 7 shows that NPL had a 4% weakening effect from machining, but MTL had a 5% strengthening. There are a number of reasons that can explain a strength difference between as-fired and machined specimens.

The as-fired specimens had a soft, silica rich, surface-reaction layer. This layer, which was about 0.02-mm thick, tended to crush and may have inhibited the rolling pin action essential to friction constraint relief in the bend fixture. Thus, the as-fired specimens would experience a friction error (that would make them appear stronger than they actually were) and the machined specimens would not. The machining should lead to apparently weaker strengths.

One other simple consequence of the surface-reaction layer is that it may not be load carrying. When the specimen is measured for its cross-section size, the dimensions would, thus, be an overestimate. If the cross section were adjusted (about 0.02 mm less from the sides), the strength would be increased by 3.8%. The strengths of the as-fired specimens would, therefore, be underestimated. Of course, the machined specimens are not subject to this factor. An apparent strengthening due to machining may be accounted for by this effect.

Fractography is a key ingredient to a proper analysis here. The majority (more than 90%) of MTL as-fired (3- and 4-point) RBSN specimens failed from **volume**-distributed flaws (usually well away from the surface). These were typically pores, unreacted silicon zones, or combinations of both. It did not matter whether specimens were from the 2510 or 2511 lot. In sharp contrast, the machined specimens broke from flaws that were, at least 50% of the time, located at the specimen surface. The flaws were usually pores which appeared different than the ones in the as-fired (volume-distributed) specimens. Thus, it would seem that there is a change in flaw population, or an alteration to the flaws that contributed to strength differences.

Finally, it should be noted that the as-fired specimens were mostly (2/3) from the 2510 lot, whereas the machined specimens were exclusively from 2511.

In conclusion, there are sufficient conflicting factors operative here to make a generalization difficult, other than to observe that there was no major change in strength.

Issue #7: Was humidity a factor?

Stress corrosion, due to water in ambient air, is known to have a potentially significant effect upon strength, even in fast fracture tests. McMahon showed a very strong effect at room temperature on a high alumina ceramic.[14] Most of the laboratories in the present exercise did measure humidity. MTL used a sling psychrometer. (The other laboratories did not report their measurement procedure.)

The results are shown in Figures 9 and 10. Results are only shown for instances where more than one humidity-strength outcome was available for a common test and specimen type. Thus, there were five humidity-strength outcomes for the labs that performed testing on the alumina in 4-point bending according to MIL STD B.

Humidity had no discernible effect on either the alumina or the RBSN.

Issue #8: What did fractography reveal?

The focus of this exercise was upon mechanical testing procedures. As such, detailed fractography was not mandated, but was highly encouraged. In practice, only a few of the laboratories had the resources to perform follow-up fractography. Time and manpower shortages were the limiting factors. Experience and expertise was less of a factor, except for several of the laboratories that were newcomers to such testing. The two materials chosen for this exercise were studied carefully in preliminary work, which was intended to evaluate the suitability of the materials for a round robin. A key ingredient in the preliminary work was very detailed fractography. Indeed, one of the criteria for choice of a material for the round robin was that it be conducive to fractographic interpretation. Both materials left clear markings that indicated the origin of failure. Strength-limiting flaws were readily visible with an optical microscope in most specimens. An exact clarification as to the identity or nature of the defects requires some supportative SEM work.

Fractographic observations have been incorporated into the text of this report as warranted, but it is not possible at this time to include a detailed section on fractography alone. A number of fascinating observations were made in this study. The author has argued that fractographically labelled Weibull plots are a valuable aid to interpretation.[10] It was our intention to prepare them for as many of the data sets as possible in this exercise. The personal computer software is available to incorporate the fractography into the data sets as listed in the Appendix. All of the specimens tested at MTL were examined with a stereomicroscope, and selected alumina specimens were viewed with a scanning electron microscope. Only a few RBSN specimens were examined by SEM during the preliminary round robin phase.

14. McMAHON, C. *Relative Humidity and Modulus of Rupture*. Amer. Ceram. Soc. Bull., v. 58, no. 9, 1979, p. 873.

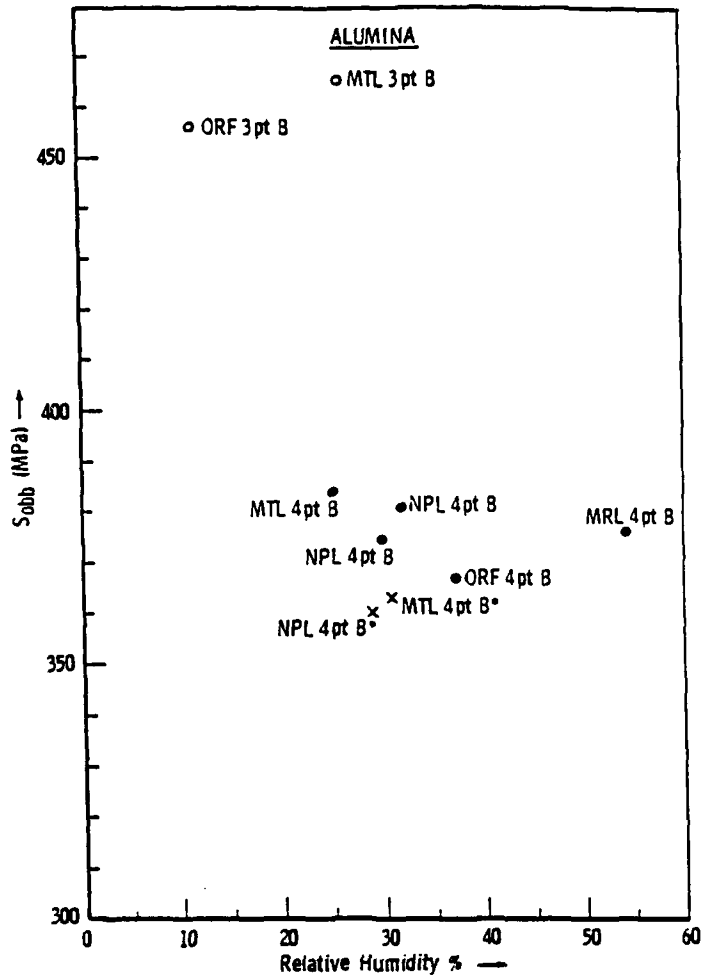


Figure 9. Sobb as a function of relative humidity for alumina. The data points represent one sampling (30 specimens), and are labelled by the laboratory, the test method, and the specimen size. B* refers to the 3-mm x 6-mm specimen.

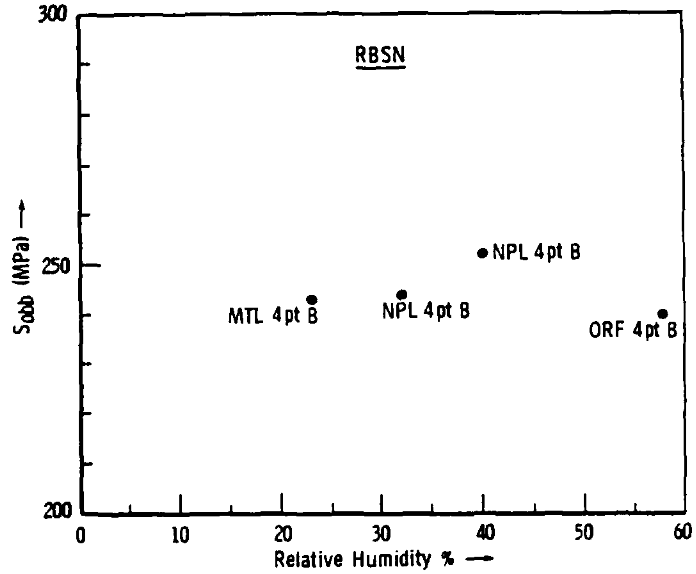


Figure 10. Sobb as a function of relative humidity for the RBSN.

Some specific conclusions and observations of fractographic work follow:

1. One preliminary lot of alumina specimens was ruined by excessive machining damage. The specimens were not used for the round robin. Machining damage caused few, or no, failures in the round robin.

2. Strength-limiting flaws were volume distributed for both the RBSN and the sintered alumina. This permitted the appropriate Weibull analysis to be used.

3. Optical examination at MTL revealed that the RBSN specimens failed from silicon lakes, pores (often associated with silicon), agglomerates, and reaction-layer defects. SEM examination is necessary to classify the agglomerates.

4. SEM and optical examinations at MTL and IITRI revealed that the alumina failed from a variety of porosity defects including: discrete voids, porous zones, porous seams, and differential shrinkage, as well as microporous zones. Further classification and characterization of these are necessary. Agglomerates, or inclusions, also caused some failures. Figures 11 through 14 show some of these defects.

5. Multiple flaw populations were active in both materials, which would complicate the statistical interpretations. Statistical analyses are available mostly for unimodal flaw populations. Unimodal-assumed analyses were used in this report. These are quite satisfactory for dealing with specimens of a common type that have been well randomized. They are less accurate for comparing specimen strengths for different sized specimens. Limited analysis work is available for multiple flaw populations.

6. In a parallel study of ceramic machining, specimens from different machine shops had different strengths. The cause was traced to billet-to-billet variations in the exact character of the flaws, and had nothing to do with machining history. (This is discussed in the Secondary Issue #9 Section which follows.)

7. The alumina and the RBSN were reasonably uniform and consistent materials, with a few exceptions. (This is discussed in the Secondary Issue #10 Section later in this report.)

8. There is a need to better label or identify defects in advanced ceramics. A common nomenclature, such as suggested in Reference 10, would be very helpful. This came up repeatedly for the aluminas, especially for the porosity-related flaws. This porosity had, as its source, powder irregularities from the green state. Once sintered, this porosity could manifest itself as discrete round holes, irregular voids, equiaxed zones of locally high microporosity, irregular zones of microporosity, or seams of planar microporosity. Combinations of these occurred as well. Thus, precise categorization was not possible in many instances. Triangular or tetrahedral seams and cracks (without porosity) were also detected that suggest micro-residual stresses or planes of weakness associated with nonuniform sintering. In general, it was possible to detect these flaws with an optical examination, however, SEM was required to accurately assess their character. Table 8 attempts to categorize the flaws by type, but cannot be definitive, since SEM examination of every specimen would have been required to be truly correct.

This variation in the character of the porosity-sintering defects is a serious matter since it could arise from subtle variations in powder processes that may be difficult to control. The variability may be sufficient to cause significant changes in the strength results, however. This was a decisive factor in an auxiliary experiment to the round robin and will be discussed in the next section.

A very similar discussion of flaw variability is given in Reference 15 for a sintered silicon nitride. In that study, the dominant flaw was categorized as a pit/white spot. The defect was named for its optical appearance in low power stereomicroscopy. The pit was a discrete void. The white spot was a pore filled with silicon nitride grains that scattered light, creating contrast with the darker matrix. Both had their roots in density inhomogeneities from cold isopressing the powders. These would sinter at differential rates. Furthermore, these non-uniformities could manifest themselves as seams or jogs in the path of a crack. The investigators in Reference 15 were ultimately able to control or eliminate this defect by altered powder processing procedures.

9. Preliminary assessments by optical microscopy were occasionally misleading or wrong (even by experts). This usually would be detected during SEM examination. In general, the accuracy of an optical assessment depends upon a number of factors including:

- Operator experience
- Operator patience and care
- Material suitability and conduciveness to analysis
- Equipment quality
- Lighting
- Luck

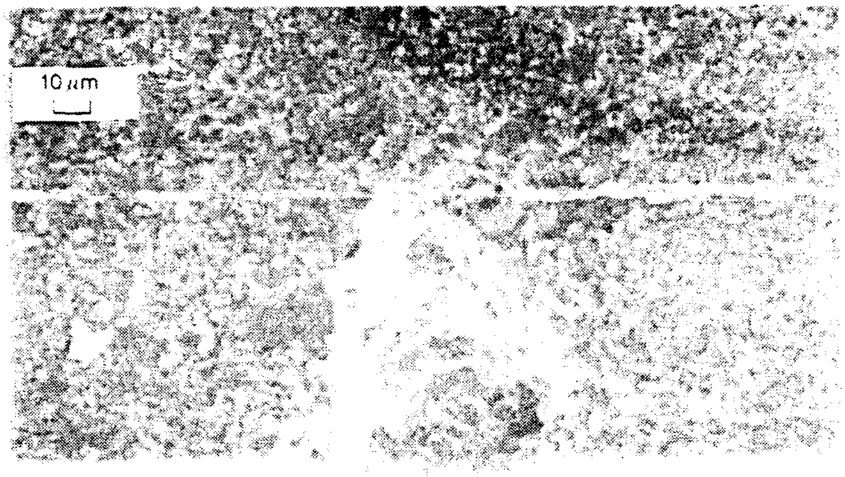
It may be somehow necessary to assign a confidence factor to the characterizations of defects. SEM work could be used to verify the optical work, or to increase its confidence. Even SEM examination is not foolproof, however, especially when the defects cannot be uniquely categorized as discussed above.

10. It is prudent to examine all specimens in a sample since a limited examination can be very misleading.

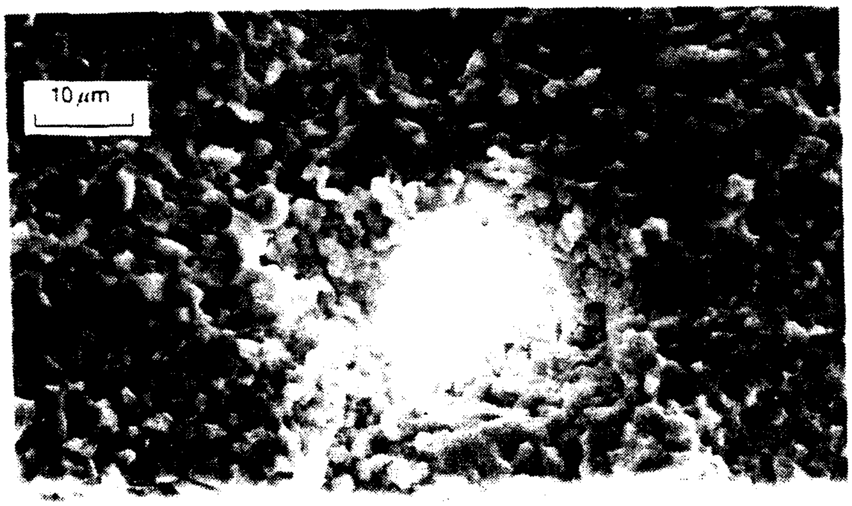
11. In a few instances, it was determined that "stray," or "outlier," data points were due to unique or exceptionally rare defects. These data could be discounted in the interest of making the strength comparisons between samples.

12. Machining the surface-reaction layer off of the RBSN changed the flaw population.

15. PASTO, A. E., NEIL, J. T., and QUACKENBUSH, C. L. *Microstructural Effects Influencing Strength of Sintered Silicon Nitride* in Ultrastructure Processing of Ceramics, Glasses and Composites, L. Hench, and D. Ulrich, ed., John Wiley and Sons, New York, 1984, p. 476-489.

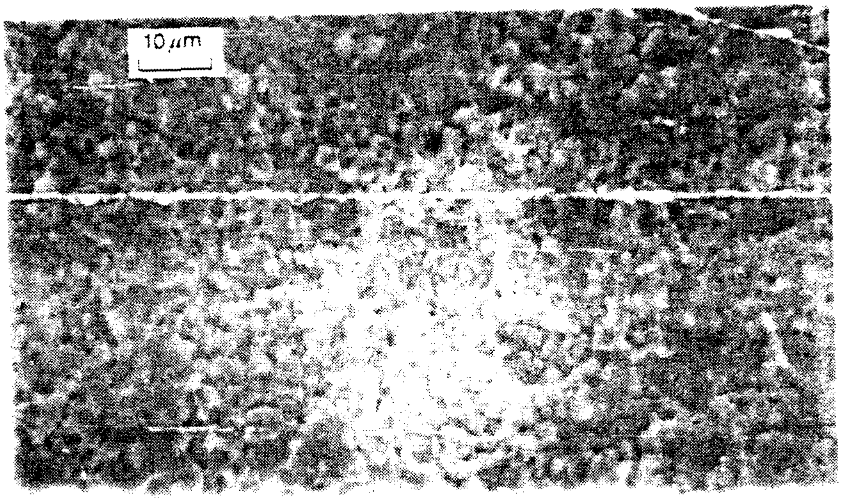


(a)

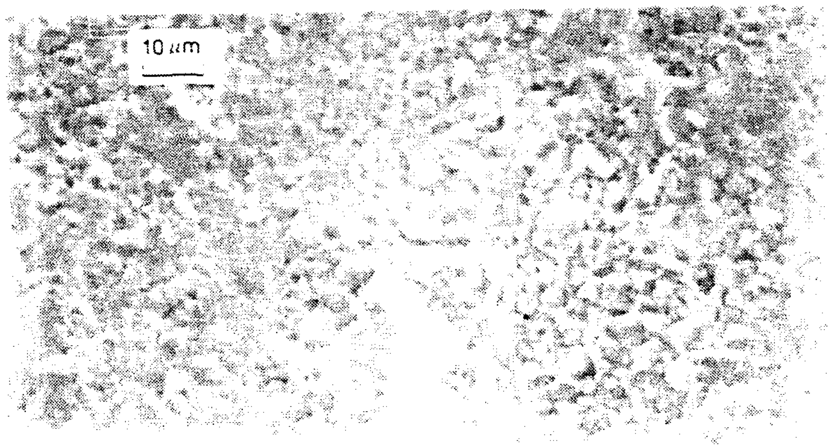


(b)

Figure 11. Pores that were strength limiting in the sintered alumina.

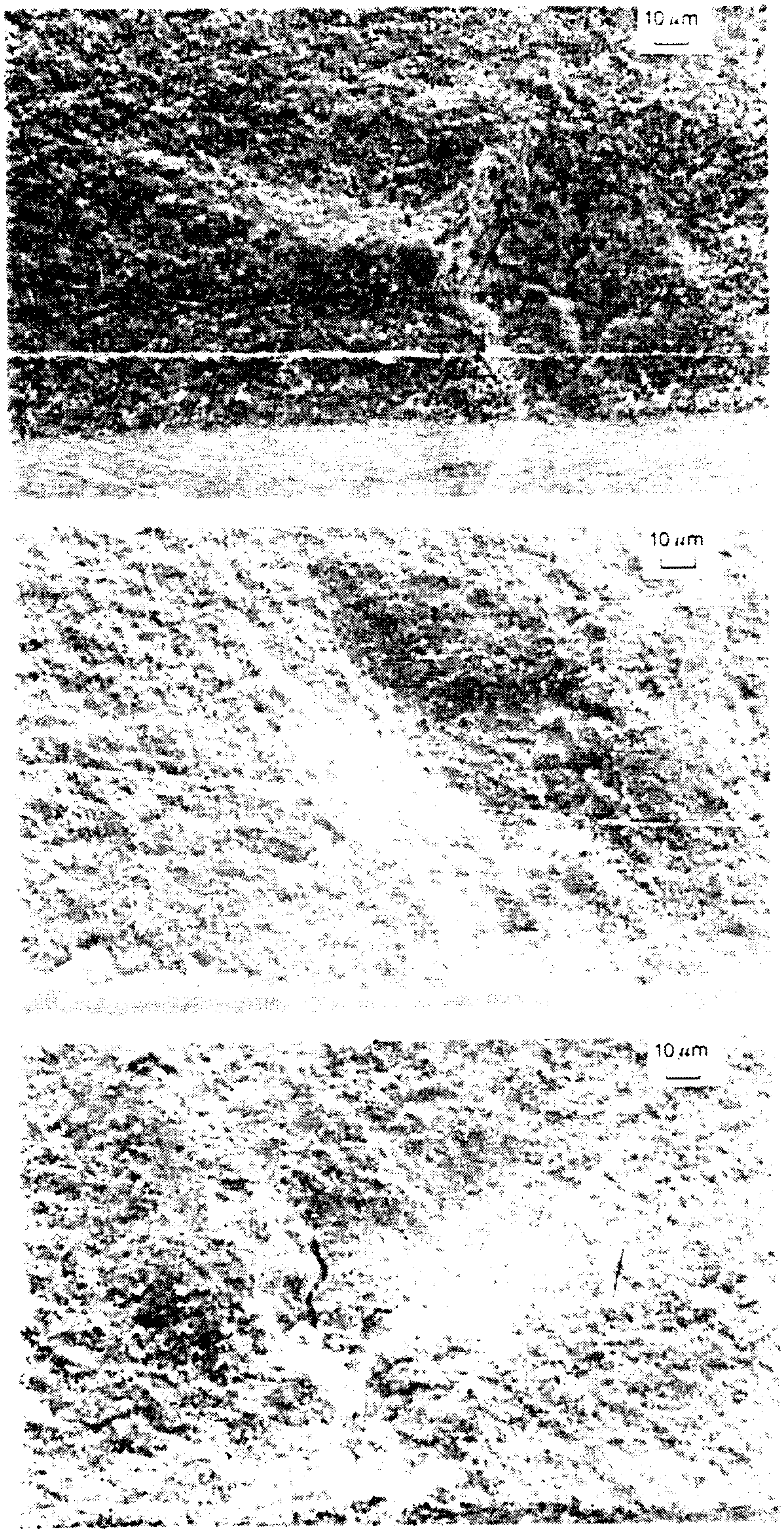


(a)



(b)

Figure 12. Porous zones that were strength limiting in the sintered alumina. Both have regions of localized high concentrations of microporosity. Shot (a) has a void area as well, making it difficult to characterize.

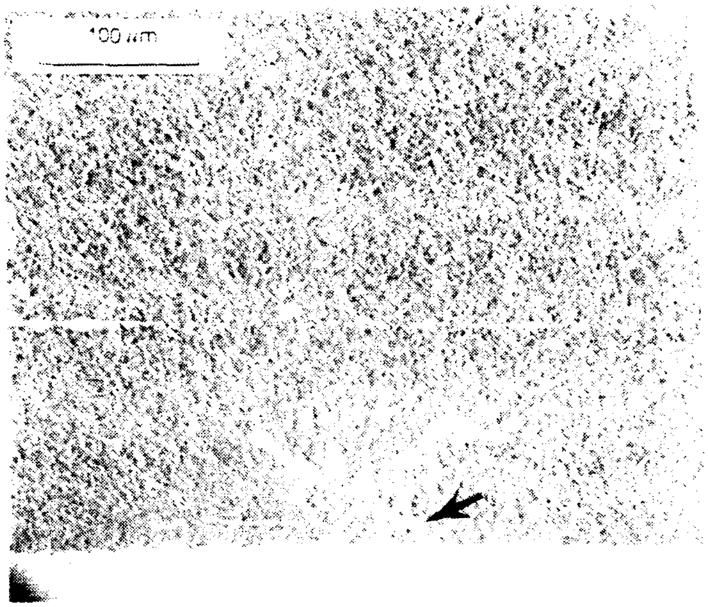


(a)

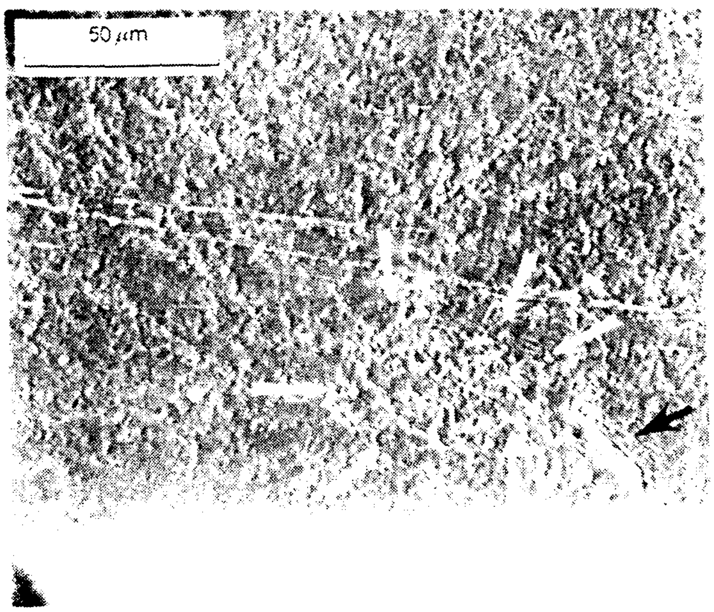
(b)

(c)

Figure 13. Porous seams that were strength limiting in the sintered alumina. The seams are either planar zones of microporosity or are cracks (or latent cracks) due to nonuniform shrinkage during sintering. Shots (b) and (c) are matching halves of one specimen.



(a)



(b)

Figure 14. A composite defect that was strength limiting in the sintered alumina. Machining damage (black arrow) has interacted with a porous zone (white arrows) beneath, but near, the specimen surface.

Table 8. PHOTOGRAPHIC SUMMARY OF ALUMINA SPECIMENS TESTED AT MTL
ALL EXAMINATIONS OPTICAL ONLY UNLESS OTHERWISE STATED

Material	Spec. Size	Method	A	Gl	I	LG	MD	P	PZ	PS	S	Uncertain	Comments
Alumina	Billets 6 - 13												
	3 mm x 4 mm	4 pt (MIL STD B)	9	1	1		2	4			5	9	A are White Fine-Grained Spherical Clumps, Seams Don't Look Porous, They are Planes of Weakness or Local Shrinkage Cracks
	3 mm x 4 mm	3 pt (MIL STD B)	4					1	5		14	[illegible]	Same as Above, SEM Analyzed
	3 mm x 6 mm	4 pt (MIL STD B)	10	2	1			3	1		11	2	Same as Above, SEM Analyzed
	1.5 mm x 2 mm	4 pt (MIL STD A)	5			1		4			8	14	Defects Seem Smaller Then in Above Samples
	6 mm x 8 mm	4 pt (MIL STD C)	17	1				6	4		1	4	Agglom. Often Associated with Pores up to 200 υm in Size, Porous Zones Usually Spherical, Pores are Spherical, Usually with Some Gloss
Alumina, Preliminary Experiments													
	3 mm x 4 mm	4 pt (MIL STD B)	3		1	1	2	10	5	3		5	Equiaxed Pores and Seams of Porosity
Alumina, Comparative Machining Study													
Billet 2	3 mm x 4 mm	4 pt (MIL STD B)	4		1		2		11	2	1	1	PZ Usually Means an Irregularly Sintered Zone, Some SEM Analysis
Billet 4	3 mm x 4 mm	4 pt (MIL STD B)	4		1		1	9	2	1		2	Very Different From Sample Immediately Above, All Flaws Equiaxed in This Instance, Some SEM Analysis
Billet 1	3 mm x 4 mm	4 pt (MIL STD B)	3		1			2	14				Seams Often Around Porous Zones, Some SEM Analysis
Billet 3	3 mm x 4 mm	4 pt (MIL STD B)	5				1		5	4		6	Some Nonuniform Sintering or Shrinkage Cracks, Some SEM Analysis

Flaw Key:

A	Agglomerate	A Clump of Sintered Alumina
Gl	Glass	A Local High Concentration of Glass
I	Inclusion	An Impurity
LG	Large Grain	
MD	Machining Damage	
P	Pore	A Discrete Void or Hole
PZ	Porous Zone	A Local Concentration of Microporosity, Not a Discrete Hole
PS	Porous Seam	A Subset of PZ, a Concentration of Microporosity That is Planar or Seamlike. Probably From Differential Sintering
S	Seam	A Planar Defect that Doesn't Necessarily Look Anymore Porous Than the Bulk. Probably From Nonuniform Sintering or Residual Stresses
	Uncertain	Too Small to Detect Optically and Not Examined by SEM, Contaminated, Pieces Lost, etc.

Issue #9: Can different machine shops produce satisfactory flexure specimens?

Machining preparation can have a profound effect upon flexure strength. Machining can introduce unwanted flaws or residual surface stresses. Specification of a final surface finish is not adequate since machining damage cracks can extend well below the surface striations. Lapping or polishing may remove surface striations, but not enough material to eliminate deeper strength-limiting machining damage.

Indeed, one lot of over 800 alumina specimens was ruined by a vendor in this exercise as has been previously discussed. (The specimens were supposed to have been prepared in accordance with MIL-STD-1942 requirements, and detailed specifications were given.) These damaged specimens were not used for the round robin. The specimens used were prepared by a reliable vendor who has made such specimens for over 25 years. Machining damage caused few, if any, failures in the round robin. Specimens failed from the inherent material defects.

To pursue this matter further, MTL conducted a parallel study to the TTCP round robin. Seven machine shops were contacted and asked to machine trial lots of 20 alumina, MIL STD B flexure specimens. The alumina used for this exercise was from the four billets delivered separately by Coors (the lot that we had set aside). These billets had been set aside for fear that they might not be consistent with the main lot used in the round robin. Only 20 specimens were required in order to keep within cost constraints, and it was hoped that 20 would be enough to discern machining problems. Preliminary results of this study were reported earlier,[10] but additional results are included herein.

All flexure testing was done at MTL in 4 point in accordance with MIL STD B. The results are shown in Table 9. Shops B through E have previously prepared flexure specimens, but for some, this was the first exposure to the requirements of MIL-STD-1942. Shop A prepared the specimens for the main round robin exercise and is included for comparison. The results for shop A were from the preliminary lot of alumina. Shops F and G were not contracted since their prices were substantially out of line. The strength results for shop D may be inaccurate since an alignment error was detected in the fixtures partway through the testing of that lot.

An initial visual inspection showed that the new vendors (B-E) did, for the most part, meet all specifications. Machining damage can be hidden, however, and strength testing and detailed fractography is necessary. A comparison of the strength values suggests that vendors B and C have somehow seriously damaged their specimens. The high Weibull modulus on vendor B's specimens also suggests that the machining damage was uniform. It would be tempting to qualify or reject the vendors on the basis of the strength data, but the fractography revealed a different story.

Table 9. RESULTS OF COMPARATIVE MACHINING STUDY

Shop	Cost/Bar	Specifications Met?	Strength Factors (MPa) Billet	Avg.	Std. Dev.	Modulus	S_{obb}	Fractography
A	$15	Yes	#P	372	42	10.3	391	Round Pores, Porous Zones, Porous Seams, Two Mach. Dam.
B	$19	Mostly Yes, Minor Edge Chips, Some Skip Striations	#2	315	22	17.1	325	Porous Zones, Porous Seams, Agglomerates, Four Mach. Dam.
C	$20	Yes, Chamfers a Bit Uneven	#1	301	30	11.5	314	Tetrahedral Shrinkage Porous Seams, Pores, Agglomerates
D*	$41	Yes, Some Striations, Not Enough Material Removed on Last Passes	#3	335	32	12.0	350	Porous Seams, Porous Zones, Agglomerates
E	$50	Yes, Rare Long Deep Striations	#4	373	36	11.9	389	Round Pores, Agglomerates Two Mach. Dam.
F	$101	Not Contracted						
G	$112	Not Contracted						
H	No Bid	Not Contracted						

*The strength results for vendor D are possibly inaccurate; see text

Detailed optical and SEM examination of the fracture surfaces revealed that machining damage was not the prime factor in any of the sample lots. Machining damage did cause failure in a few specimens, but strength-limiting flaws were typically volume-distributed sintering defects such as pores, porous zones, porous seams, agglomerates, and inclusions, as shown in Table 9. The critical difference was that the exact nature of these flaws and their distribution varied from billet to billet. Careful records were kept in this regard. Table 9 shows that there was a subtle difference in flaw character. Porosity, the most common failure origin, manifested itself as discrete round pores, equiaxed zones of microporosity, planar seams of microporosity, differential shrinkage porous seams, or pores associated with inclusions. The tendency for each form varied between billets. Billets 1 through 4 were prepared from the same powder lot by an identical procedure and were, to all appearances, identical. Only when specimens were fractured could the true flaw character be assessed.

In summary, this exercise illustrates the hazards of interpreting flexure strength results without supportative fractography. Machining damage was not a factor in the parallel study, and four new vendors have been qualified for flexure specimen preparation. Material consistency was a problem.

Issue #10: Are there lot-to-lot variations of strength in the materials?

This issue is, in essence, a matter of material consistency. Comparisons of strength results on advanced ceramics have inevitably raised this issue. The two materials used in this exercise were carefully and deliberately chosen because they were relatively consistent and uniform. Statistical analysis of the strength results was based upon this premise, as previously discussed. With all testing completed, and all analyses performed, it is prudent to reexamine this key assumption.

The alumina specimens for the main round robin were prepared from 4" x 4" x 1" billets, as previously discussed in the Materials Section of this report. All indications were that the billets were uniform and consistent, even though they arrived in three different lots. All billets were certified by the vendor.

The first lot of billets was used for the preliminary phase of the exercise only. Most of the material was lost when a vendor ruined 800 specimens.

Additional material was ordered, but arrived in two lots; a group of four and a group of nine billets. It was determined during the machining study that the material in the group of four billets was not consistent since there was wide strength scatter that was traced to subtle variations in flaw type.

Alternatively, the strengths of the first lot (Figure 4) and the last lot of nine billets were similar. The strengths in the latter were somewhat higher than the former, although the Weibull moduli are extremely consistent. Fractography indicated that the flaws were of identical type.

Subtle differences in the flaw type are possible from billet to billet, or within a given billet. This variability **could only be assessed by detailed fractography of broken specimens.** (Very careful polished-section metallography may help, however. Such analysis would be aimed, not at the typical microstructure, but for extreme features that reflect the strength-limiting flaws in the material.) This does not bode well for the ceramics design community, and suggests statistics of material nonuniformity may have to be superimposed upon the typical Weibull flaw variability. Even the latter is complicated by the presence of multiple flaw populations. Of course, the randomization scheme (riffling) eliminated any variations in this study **within any given specimen type.**

The conclusion that must be reached is that the sintered alumina ceramic used in this exercise had a uniformity that is typical for advanced ceramics, but that subtle flaw population variability can exist.

The RBSN was available in three green billets, and two nitridation runs (2510 and 2511). Several different specimen sizes were prepared and nitrided as well: 3 mm x 4 mm, 4.5 mm x 4.5 mm, and the oversized versions intended for the surface machining inquiry. The density of all lots were very consistent, averaging 2.40 g/cm^3 with standard deviations of only 0.01 g/cm^3.

Specimens from the first billet were made only to the size of 4.5 mm x 4.5 mm. Two samples of 30 specimens only were prepared. One sample was nitrided in the 2510 run, and the other in the 2511 run. These specimens were then fractured in 3-point loading by ARE in their current 3-point fixtures. Table 10 shows the results (which have previously been discussed in Issue #4, Experiment #2).

Table 10.

	ARE Current 3 pt, Lot 2510	ARE Current 3 pt, Lot 2511	Avg. of Lots 2510 and 2511
S_{avg}	278	292	
Std. Dev.	23	26	
m	14.5	12.8	13.6
S_{obb}	288	304	296

The values of box m and S_{obb} are quite consistent, and there seems to be no difference between the true strength parameters of nitridation runs 2510 and 2511 (Figure 3a). Based upon this, the remaining specimens were randomized and distributed to TTCP participants. Most samples of 3-mm x 4-mm specimens were uniformly composed of 2/3 specimens from lot 2510 and 1/3 from lot 2511. (On the other hand, ARE tended to test lots exclusively in 2510 to 2511.)

The analysis of Issue #4, Experiment #2, raised a few questions about whether the specimens from the billets for the bulk of the exercise had strengths consistent with specimens from the single billet used for the preliminary 4.5-mm x 4.5-mm experiments described in the previous paragraph.

Some of the other laboratories kept track of the 1510 and 2511 specimens, and some clear conclusions can be drawn.

ORF tested one lot of 3-mm x 4-mm specimens in 4 point according to MIL-STD-1942 procedure with the following result:

	Lot 2510	Lot 2511
S_{avg}	235	234
Std. Dev.	12.7	9.9
m	21.4	23.4
S_{obb}	241 (20 Spec.)	239 (10 Spec.)

There is obviously no difference.

Similarly, on a group of 3-mm x 4-mm specimens tested in 3-point bending according to MIL-STD-1942, MTL observed:

	Lot 2510	Lot 2511
S_{avg}	268	266
Std. Dev.	13	14.9

The Weibull parameters were not computed in this instance, but it is evident that the two lots were again very consistent.

NPL compared the two lots in two data samples, both being in 4-point loading for 3-mm x 4-mm specimens. For the new MIL-STD-1942 fixtures:

	Lot 2510	Lot 2511
S_{avg}	241	256
Std. Dev.	11.2	12.7
m	22.9	19.5
S_{obb}	–	–

Both m and the strength location parameter S_{avg} are very consistent in this instance. For the old NPL fixtures (which are MIL-STD-1942 compatible):

	Lot 2510	Lot 2511
S_{avg}	232	246
Std. Dev.	18.4	11.5
m	12.9	20.6
S_{obb}	–	–

The lot 2510 results, here, were not well behaved on the Weibull graph. Two unusually low, and one unusually high strength specimen tended to make the scatter too high and the Weibull modulus low. If these data were deleted, the results would be consistent.

Thus, the evidence indicates that specimens from two billets, nitrided in runs 2510 and 2511, were very consistent. The vast majority of specimens for the round robin came from these two billets. The remaining billet was only used for preliminary experiments with 4.5-mm x 4.5-mm specimens at ARE, and it is not clear if it was consistent with the other two billets.

Finally, RBSN lot 2463 was used for preliminary evaluation in November, 1984. The 4-point strengths measured at MTL according to MIL STD B were:

	Lot 2463	Lots 2510 and 2511
S_{avg}	230	237
Std. Dev.	19	13
m	14.3	21.7
S_{obb}	238	243

These results are also very consistent, although the lot 2463 modulus is low. Fractography indicated that the same flaws were responsible for failure for both lots.

In summary, the RBSN was quite consistent. The lowest Weibull modulus for the RBSN was of the order of 10; the more typical values were 20 or more. Many manufacturers of advanced structural ceramics would envy these results.

Summary

This summary condenses the results given in the previous section.

Key Issues

1. Using a common procedure, can different laboratories measure flexure strength accurately and precisely?

Exp. #	Material	Spec. Size	Test Method	No. of Labs	Results
1	Alumina	3 mm x 4 mm	4 pt, MIL STD B	6	4 of 6 Labs Consistent
2	Alumina	3 mm x 4 mm	3 pt, MIL STD B	3	2 of 3 Labs Consistent
3	Alumina	3 mm x 6 mm	4 pt, MIL STD B*	3	Yes
4	RBSN	3 mm x 4 mm	4 pt, MIL STD B	5	Yes for m, S_{obb} Consistent for 3 Labs
5	RBSN	3 mm x 4 mm	3 pt, MIL STD B	2	Yes
6	RBSN, Mach.	3 mm x 4 mm	4 pt, MIL STD B	2	Yes for m

Net Conclusion:

With a few exceptions, the results are consistent when performed by MIL-STD-1942 procedure.

2. Does the 3-mm x 6-mm specimen give satisfactory results relative to the 3-mm x 4-mm configuration?

Exp. #	Material	Test Method	No. of Labs	Result
1	Alumina	4 pt, MIL STD B*	3	Yes

Net Conclusion:

The results were very consistent.

(The 3-mm x 6-mm specimen may have slightly higher twisting error in some cases, but not in this instance, for well-machined specimens.)

3. Given a constant specimen size (3 mm x 4 mm), are "old" or "current" test fixtures giving results consistent with MIL-STD-1942 test fixtures?

Exp. #	Material	Test Method (Spans)	Results
1	Alumina (Prelim.)	MTL, 4 pt, Fixed (1.6" x 0.8")	No, Friction Error
2	Alumina (Prelim.)	NRL, 4 pt, Old Fixture	No, Friction Error
3	Alumina	IITRI/AFWAL, 4 pt, Current (1.75" x 0.875" Modified to 40 mm x 20 mm)	Probably No
4	Alumina	ARE, 4 pt, Current (40 mm x 19 mm)	m Consistent, S_{obb} Too High
5	Alumina	ARE, 3 pt, Current (40 mm)	m Consistent, S_{obb} Too High
6	Alumina	NPL, 4 pt, Current (40 mm x 20 mm)	Yes
7	RBSN	IITRI/AFWAL, 4 pt, Current (1.75" x 0.875" Modified to 40 mm x 20 mm)	m Not Consistent, S_{obb} Consistent
8	RBSN	NPL, 4 pt, Current (40 mm x 20 mm)	Yes
9	RBSN	ARE, 3 pt, Current (40 mm)	m Not Consistent, S_{obb} Consistent
10	RBSN	ARE, 4 pt, Current (40 mm x 19 mm)	Similar Curves, but Position Shifted

Net Conclusion:

Sporadic results were obtained here. Every lab except NPL had some problem with their old or current fixtures. The NPL fixtures are virtually MIL-STD-1942 compatible anyway, so it is not surprising that their results were consistent, both for the RBSN and the alumina.

4. Are "old" or "current" practices (different fixtures and specimens) giving results comparable to MIL-STD-1942?

Exp. #	Material	Lab	Method	Spans	Specimen	Result
1	Alumina	IITRI/AFWAL	4 pt	1.75" x 0.875"	1/8" x 1/4"	m Consistent, Sobb Consistent to 3 mm x 6 mm, Not With 3 mm x 4 mm Specimen Data
2	RBSN	ARE	3 pt	40 mm	0.18" x 0.18"	Lot-to-Lot Variance Interferes With Interpretation

Secondary Issues

5. Does a Weibull size analysis apply to the strength data?

A sufficient range of sizes existed for the alumina to investigate this issue. MIL STD B specimen testing produced good Weibull size correlations, but multiple flaw populations and billet-to-billet consistency interfered with comparisons to other specimen sizes.

6. Does machining the reaction layer off of the RBSN alter the strength?

MTL observed a 5% strength enhancement, but NPL had a 4% weakening. There was no major strength change, however. A number of factors could account for the different results here.

7. Was humidity a factor?

Humidity was not a factor for either the alumina or the RBSN.

8. What did fractography reveal?

Fractography was not mandatory in this exercise, but was valuable in several instances. Strength-limiting flaws were volume distributed and multimodal for both materials. The multimodal issue complicates comparison of strengths of different sized specimens.

Fractography confirmed that machining damage ruined one lot of alumina specimens. On the other hand, in a parallel study, fractography indicated four new machine shops could satisfactorily make specimens.

Billet-to-billet variations in the alumina and as-fired versus machined variations in the RBSN were traced to subtle flaw population changes.

Opportunity permitting, it may be possible to do more fractography on this excellent data base and incorporate it into the data files. The goal would be to create the most comprehensive and accurate data base of strength for advanced ceramics ever documented. This data base would be extremely valuable to statisticians and brittle materials designers.

9. Can different machine shops produce satisfactory flexure specimens?

Five machine shops were able to meet the specifications of MIL-STD-1942 (MR) on a sintered alumina. One experienced shop met all of the specifications, and was used to make the bulk of the specimens for the round robin. Four new vendors did good work, but there were minor faults in each case. One vendor ruined 800 specimens by creating excessive machining damage.

10. Are there lot-to-lot variations of strength in the material?

The sintered alumina had good uniformity and is typical of advanced ceramics. Subtle flaw variations between billets from one lot were observed in the comparative machining study. Within the main round robin exercise, flaw variation may have interfered with comparisons of strength of different sized specimens. The preliminary alumina lot tended to have higher strength than the lot used for the main round robin exercise.

The RBSN was quite uniform and no variability was observed between nitridation runs 2510 and 2511. Results from preliminary work on specimens from lot 2463 gave very consistent results as well. Two samples with specimen sizes of 4.5 mm x 4.5 mm, which were taken from a different billet, may have had different strengths.

CONCLUSIONS

The round robin exercise was very successful. Most of the issues raised could be unequivocally answered as demonstrated in the previous section. This is unusual. Many round robins conclude by raising as many questions as they answer (e.g., Reference 16).

The round robin was devised in order to address some fundamental issues regarding strength testing of advanced ceramics. In the past, flexure testing has been widely performed for quality control or materials development purposes. As advanced ceramics mature, it is necessary that testing methods also improve so that they yield high quality, accurate, and consistent data. The U.S. Army military standard, MIL-STD-1942 (MR), *Flexure Strength of High Performance Ceramics at Ambient Temperature* (1983), was developed by MTL to serve this requirement. TTCP panel members debated the value of MIL-STD-1942, and questioned certain aspects of it. It was jointly agreed to conduct a round robin exercise to specifically investigate and verify some of the issues raised.

Flexure strengths measured by MIL-STD-1942 were, for the most part, very consistent, both for the RBSN and the sintered alumina. This is a crucial and positive outcome. The modified MIL STD B configuration with a 3-mm x 6-mm cross section (that is a 1:2 aspect ratio) produced good results for the sintered alumina, thus vindicating the stance of the U.S. Air Force and IITRI. Older test procedures generally gave results that were less satisfactory for one reason or another. In several instances (MTL and NRL in particular), faulty older procedures or fixtures were uncovered.

The validity of the strength comparisons hinges upon control over, or an understanding of, all possible sources of scatter in results. Scatter can result from:

16. RITTER, J. JR., SERVICE, T., and GUILLEMET, C. *Strength and Fatigue Parameters for Soda-Lime Glass.* Glass Technology, v. 26, no. 6, 1985, p. 273-278.

- Experimental flexure testing error
- Material nonuniformity
- Inherent statistical variability of taking limited sized samples for unimodal flaw populations
- Additional statistical variability due to multiple flaw populations

The two materials chosen were very uniform for advanced ceramics, yet some doubt existed. In a couple of instances, inconsistent material probably did occur. Fractography was essential to make this appraisal. The nonuniformity could usually be traced to flaw changes. The potential nonuniformity primarily manifested itself when comparisons of different sized specimens were made.

The inherent strength scatter can be estimated with a high confidence by analyses in the literature. The statistical analysis used was relatively simple, but was extremely valuable. Indeed, the results of this study, in turn, tend to support the validity and usefulness of the statistical analyses. A critical assumption that must not be overlooked, however, is that most of the analyses are for a unimodal flaw population. The alumina and RBSN clearly had more than one flaw type active, but to the extent that these flaws are all members of one family or class, perhaps the analyses can hold up. For instance, porosity-related defects were the dominant cause of failure in the alumina. Are pores (voids) and microporous zones two different flaw types, or members of one general flaw class? It is believed that they were different in this instance, and contributed to additional variability in the results.

Strength results more deviant than expected from other samples must be considered potentially in error. Results that are not in agreement with other results are merely pointed out in most instances. Occasionally, based upon the statistics, a sample can be expected to stray from other results. Systematic deviations are of more concern, however. We do not wish to dwell on the possible shortcomings or older or customary test procedures that led to faulty or inconsistent results in this study. In many instances the problems **could** be traced to specific causes, however. For example, the erroneous results from the old fixed-pin fixture used at MTL were clearly related to the fixed points of loading. The occasionally inconsistent results at ARE and ITTRI, even when using MIL-STD-1942 procedures, were traceable to specific causes.*

A number of lessons were learned regarding round robins for advanced ceramics. First, great emphasis should be placed upon choosing materials that are uniform and consistent. This can be a problem at the current state of the art. A preliminary exercise to verify the choice of materials was critical in ferreting out other unforeseen problems. Preliminary groundwork is essential in preparing a round robin exercise.

This exercise can justifiably be criticized as being too ambitious. The test plan was devised to be responsive to the requests of the many participants and, yet, to be technically rigorous. In practice, this meant that we probably dealt with too many variables. A tighter, less diverse testing schedule may have been more technically competent and easier to analyze, but it was necessary to keep the members content in order to get a good response. Indeed, we were successful in this aspect, with six of seven participating laboratories completing all of their allotted tasks.

*For example, the ARE tests were performed at the wrong crosshead speed, as previously noted. This can influence results, as noted in Reference 14.

The entire exercise required almost 3 years to implement from its inception in August, 1984. We anticipated that it would take 1-1/2 to 2 years, but there were delays in procuring material and satisfactory specimens. Much more work than originally expected had to be done. Future round robins should keep this in mind, and should be carefully planned to enhance the chances of success.

ACKNOWLEDGMENTS

This work could not have been completed without the valuable assistance of Mr. Raymond Goulet, a cooperative education student from Northeastern University. Michael Slavin of MTL contributed valuable help at various phases of this study.

Mr. Anthony Grzan assisted by creating the Weibull software for this exercise.

Dr. Curtis Johnson of General Electric contributed with helpful statistical discussions.

This round robin would not have been successful without the hard work and cooperation of all of its participants. It is unusual for round robins to have as good a response level as was attained in this instance. Special thanks are in order to Dr. David Godfrey of the Admiralty Research Establishment for his painstaking work to fabricate the RBSN and for completing 10 data sets.

During the course of this study, TTCP panel P-TP-2 was chaired by Dr. Norman Tallan of the Air Force Materials Laboratory, Ohio, and by Dr. Keith Lewis of the Royal Signals Establishment, United Kingdom.

APPENDIX. INDIVIDUAL DATA SETS AND WEIBULL GRAPHS

The following pages list the individual data samples followed by the pertinent Weibull graph. Little or no fractography has been logged in at this time, although the information is available for many samples. The samples are in the same order as given in Table 5 in the text, which is repeated on page 61 for convenience as Table A-1.

Table A-1

				Normal		Weibull			
Material	Spec. Size	Laboratory	Method	Avg. Str.	Std. Dev.	Modulus	Ch. Str.*	Comments	Page
Alumina	1.5 mm x 2 mm	MTL (Quinn)	4 pt (MIL STD A)	372	56	7.3	397		62
Alumina	3 mm x 4 mm	ARE (Godfrey)	3 pt (ARE Fixt.)	452	63	8.0	480		64
Alumina	3 mm x 4 mm	ARE (Godfrey)	3 pt (MIL STD B)	400	25	17.8	412	10 Spec. Only	66
Alumina	3 mm x 4 mm	MTL (Quinn)	3 pt (MIL STD B)	444	51	10.2	466		68
Alumina	3 mm x 4 mm	ORF (Sullivan)	3 pt (MIL STD B)	434	51	10.1	456		70
Alumina	3 mm x 4 mm	ARE (Godfrey)	4 pt (ARE Fixt.)	378	39	11.7	395		72
Alumina	3 mm x 4 mm	IITRI (for AFWAL)	4 pt (MIL STD B)	381	32	14.4	395		74
Alumina	3 mm x 4 mm	MRL (Johnston)	4 pt (MIL STD B)	353	50	7.8	376		76
Alumina	3 mm x 4 mm	ARE (Godfrey)	4 pt (MIL STD B)	323	52	7.3	345		78
Alumina	3 mm x 4 mm	MTL (Quinn)	4 pt (MIL STD B)	364	45	9.3	384		80
Alumina	3 mm x 4 mm	ORF (Sullivan)	4 pt (MIL STD B)	347	44	8.6	367		82
Alumina	3 mm x 4 mm	IITRI (for AFWAL)	4 pt (Mod. IITRI)	365	56	7.3	389		84
Alumina	3 mm x 4 mm	NPL (Morrell)	4 pt (MIL STD B)	359	37	11.6	375		86
Alumina	3 mm x 4 mm	NPL (Morrell)	4 pt (NPL Fixt.)‡	363	39	10.5	381		88
Alumina	3 mm x 6 mm	IITRI (for AFWAL)	4 pt (MIL STD B)	362	33	13.2	376		90
Alumina	3 mm x 6 mm	MTL (Quinn)	4 pt (MIL STD B)	341	48	7.4	363		92
Alumina	3 mm x 6 mm	NPL (Morrell)	4 pt (MIL STD B)	345	34	12.3	360		94
Alumina	1/8" x 1/4"	IITRI (for AFWAL)	4 pt (0.875" x 1.750")	343	49	8.4	363		96
Alumina	6 mm x 8 mm	MTL (Quinn)	4 pt (MIL STD C)	330	35	11.0	345		98
RBSN	3 mm x 4 mm	ARE (Godfrey)	3 pt (ARE Fixt.)	265	24	13.1	276	2511	100
RBSN	3 mm x 4 mm	ARE (Godfrey)	3 pt (MIL STD B)	271	13	24.2	276	2510, 10 Spec.	102
RBSN	3 mm x 4 mm	MTL (Quinn)	3 pt (MIL STD B)	267	13	24.3	273	2510 and 2511	104
RBSN	3 mm x 4 mm	ARE (Godfrey)	4 pt (ARE Fixt.)	263	28	11.1	275	2510	106
RBSN	3 mm x 4 mm	MTL (Quinn)	4 pt (MIL STD B)	237	13	21.7	243	2510 and 2511	108
RBSN	3 mm x 4 mm	IITRI (for AFWAL)	4 pt (MIL STD B)	230	13	20.4	236		110
RBSN	3 mm x 4 mm	ORF (Sullivan)	4 pt (MIL STD B)	234	12	23.6	240	2510 and 2511	112
RBSN	3 mm x 4 mm	ARE (Godfrey)	4 pt (MIL STD B)	274	29	10.4	288	2511	114
RB[illegible]	3 mm x 4 mm	IITRI (for AFWAL)	4 pt (Mod. IITRI)	229	30	8.3	243		116
RBSN	3 mm x 4 mm	NPL (Morrell)	4 pt (MIL STD B)	246	13	22.1	252	2510 and 2511	118
RBSN	3 mm x 4 mm	NPL (Morrell)	4 pt (NPL Fixt.)‡	237	17	16.1	244	2510 and 2511	120
RBSN	4.5 mm x 4.5 mm	ARE (Godfrey)	3 pt (ARE Fixt.)	292	26	12.8	304	2511	122
RBSN	4.5 mm x 4.5 mm	ARE (Godfrey)	3 pt (ARE Fixt.)	278	23	14.5	288	2510	[illegible]4
RBSN Mach.†	3 mm x 4 mm	MTL (Quinn)	4 pt (MIL STD B)	248	17	17.5	255	2511 Mach.†	126
RBSN Mach.†	3 mm x 4 mm	NPL (Morrell)	4 pt (MIL STD B)	231	22	12.3	241	2511 Mach.†	128

*Characteristic strength of the bend bar
†Surface machined
‡MIL-STD-1942 compatible

Note: All strengths in MPa.

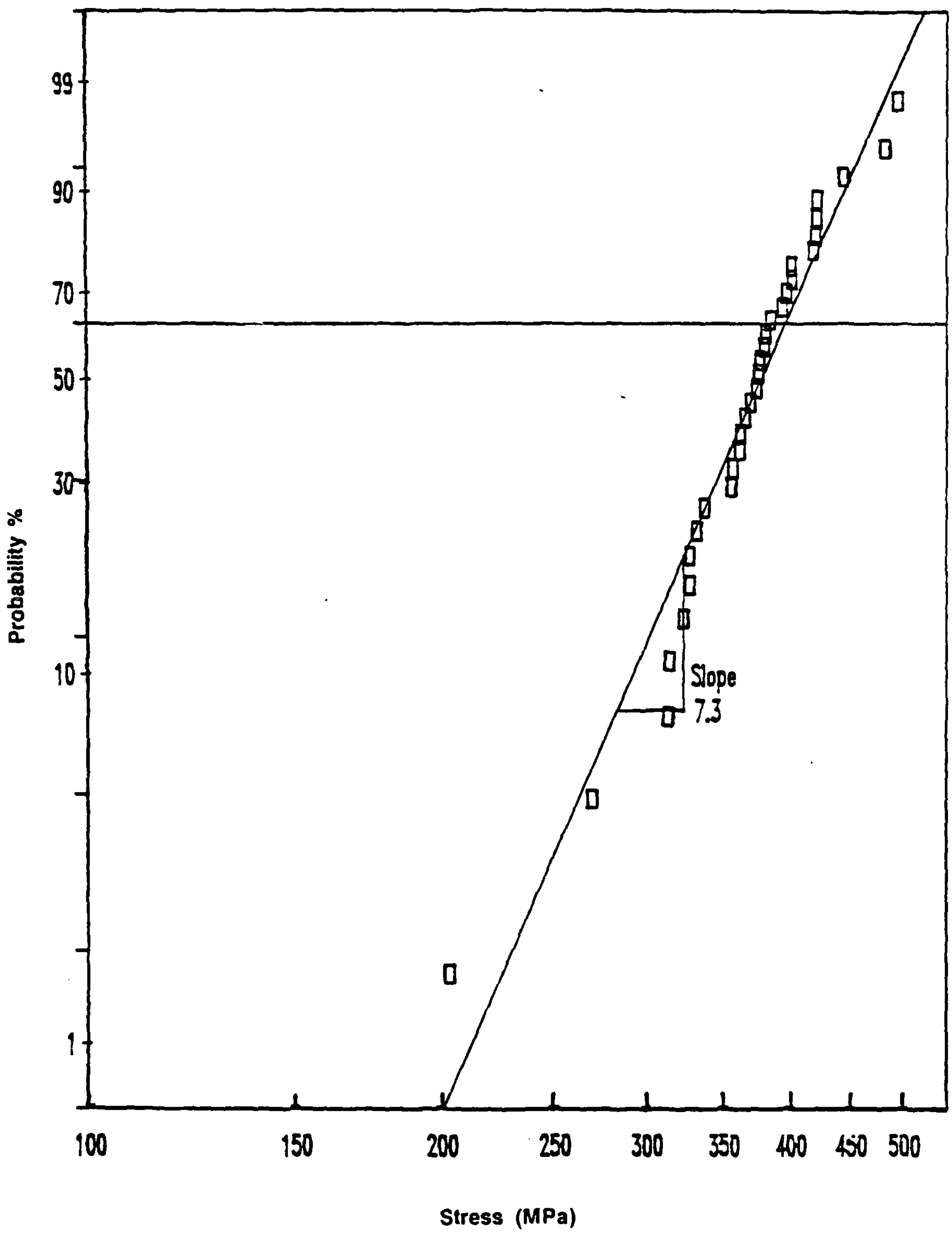
Alumina, 1.5 mm x 2 mm, 4 pt, MIL-STD-1942 (MR), MTL (Quinn)

MATERIAL	COORS AD-999	VINTAGE	1984 A1203
BILLET NO.		MILSTD 1942 (4-point)	
C.H SPEED	0.5 mm/min*	SPECIMEN SIZE	A
TEMP	79 F	Characteristic Strength	
HUMIDITY	34%	of B.B	397 MPA
TESTER	S.WESTELMAN	SLOPE	7.349
MOMENT ARM	5 mm	CHART SPEED	100 mm/min

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
9	62.0	2.002	1.511	203	29.5		NO	NO	
14	82.4	2.012	1.509	270	39.1		NO	NO	
13	96.0	2.012	1.511	313	45.5		NO	NO	
2	95.8	2.009	1.509	314	45.6		NO	NO	
10	98.8	2.012	1.509	323	46.9		NO	NO	
21	99.8	2.007	1.509	328	47.5		NO	NO	
20	99.6	2.009	1.506	328	47.6		NO	NO	
26	101.8	2.012	1.511	332	48.2		NO	NO	
17	103.4	2.012	1.511	338	49.0		NO	NO	
28	108.4	2.007	1.509	356	51.6		NO	NO	
25	107.6	1.991	1.506	357	51.8		NO	NO	
23	109.6	2.012	1.501	363	52.6		NO	NO	
24	109.8	2.007	1.504	363	52.6		NO	NO	
15	110.2	2.009	1.499	366	53.1		NO	NO	
7	112.8	2.007	1.509	370	53.7		NO	NO	
6	114.4	2.012	1.509	375	54.3		NO	NO	
27	111.8	2.007	1.491	376	54.5		NO	NO	
22	114.4	2.007	1.506	377	54.7		NO	NO	
1	116.8	2.012	1.514	380	55.1		NO	NO	
19	116.0	2.017	1.504	381	55.3		NO	NO	
31	117.2	2.007	1.509	385	55.8		NO	NO	
3	120.4	2.009	1.511	394	57.1		NO	NO	
5	120.4	1.999	1.509	397	57.5		NO	NO	
4	122.4	2.009	1.509	401	58.2		NO	NO	
29	121.6	2.009	1.504	401	58.2		NO	NO	
30	126.4	2.002	1.504	419	60.7		NO	NO	
8	127.6	2.007	1.506	420	61.0		NO	NO	
32	128.2	2.004	1.509	421	61.1		NO	NO	
12	129.0	2.009	1.511	422	61.2		NO	NO	
11	135.6	2.009	1.511	443	64.3		NO	NO	
16	147.0	2.009	1.509	482	69.9		NO	NO	
18	150.6	2.007	1.509	494	71.7		NO	NO	
				MEAN					
				372					
				STD					
				56					

*The crosshead rate used, 0.5 mm/min, was incorrect.
A rate of 0.2 mm/min was prescribed by the MIL STD "A" configuration

Alumina, 1. 5 mm x 2 mm, 4 pt, MIL-STD-1942 (MR), MTL (Quinn)



Alumina, 3 mm x 4 mm, 3 pt, Current Fixture, ARE (Godfrey)

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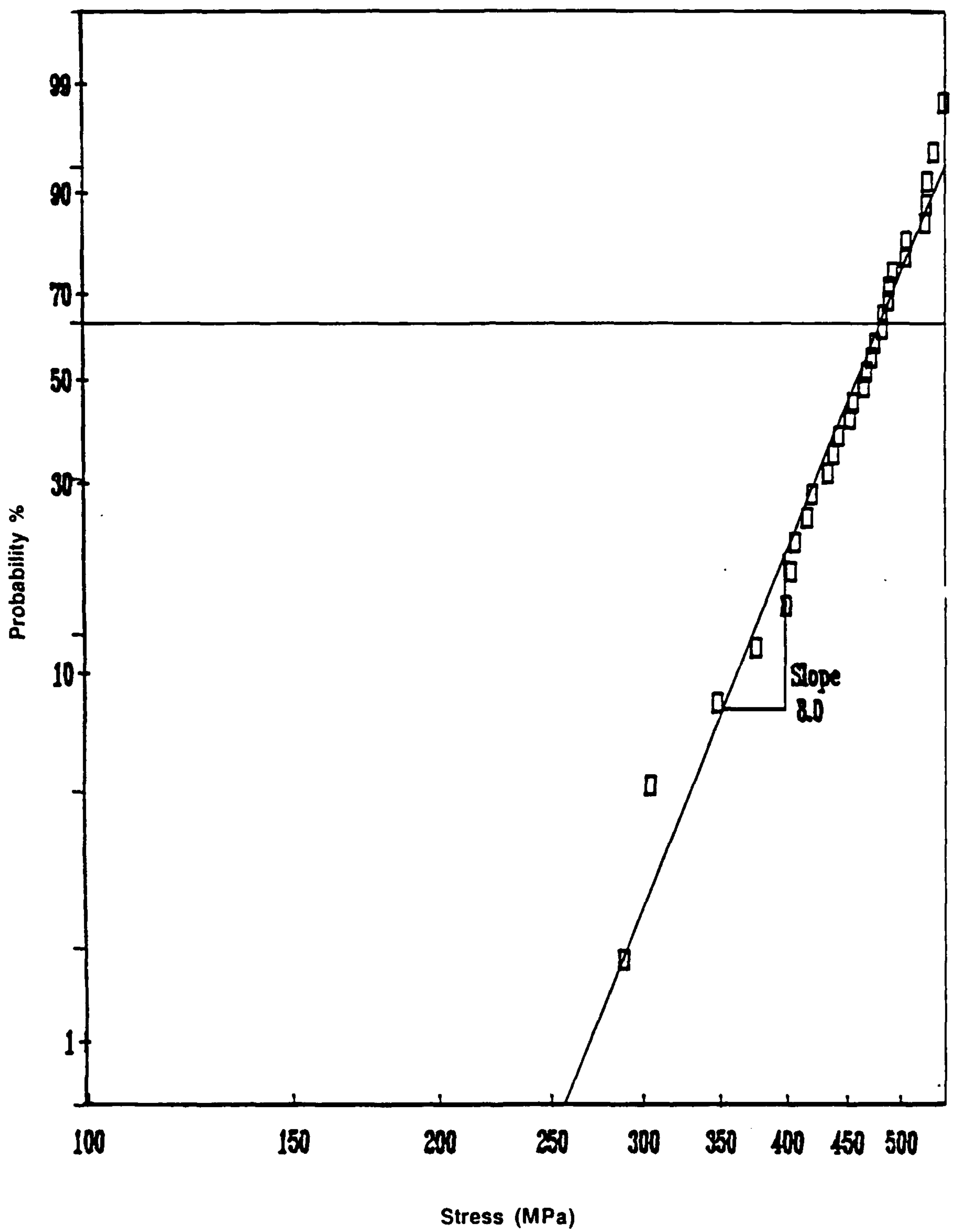
MATERIAL      AD-999              VINTAGE
BILLET NO.                        3 PT, ARE FIXTURE
C.H SPEED      2.0 mm/min         SPECIMEN SIZE   MIL-STD B, 3X4 mm
TEMP                              Characteristic Strength
HUMIDITY                          of B.B       480 MPA
TESTER                            SLOPE     7.985
MOMENT ARM        20 mm           CHART SPEED
```

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
1	N/A	4.0	3.0	289	41.8				
2	N/A	4.0	3.0	304	44.1				
3	N/A	4.0	3.0	348	50.4				
4	N/A	4.0	3.0	376	54.5				
5	N/A	4.0	3.0	399	57.9				
6	N/A	4.0	3.0	404	58.5				
7	N/A	4.0	3.0	406	58.9				
8	N/A	4.0	3.0	417	60.4				
9	N/A	4.0	3.0	420	60.9				
10	N/A	4.0	3.0	434	62.9				
11	N/A	4.0	3.0	438	63.5				
12	N/A	4.0	3.0	443	64.2				
13	N/A	4.0	3.0	452	65.6				
14	N/A	4.0	3.0	455	65.9				
15	N/A	4.0	3.0	465	67.3				
16	N/A	4.0	3.0	467	67.7				
17	N/A	4.0	3.0	472	68.4				
18	N/A	4.0	3.0	475	68.8				
19	N/A	4.0	3.0	483	69.9				
20	N/A	4.0	3.0	483	69.9				
21	N/A	4.0	3.0	488	70.7				
22	N/A	4.0	3.0	489	70.8				
23	N/A	4.0	3.0	492	71.3				
24	N/A	4.0	3.0	505	73.2				
25	N/A	4.0	3.0	505	73.2				
26	N/A	4.0	3.0	524	76.0				
27	N/A	4.0	3.0	525	76.2				
28	N/A	4.0	3.0	526	76.2				
29	N/A	4.0	3.0	533	77.2				
30	N/A	4.0	3.0	544	78.8				
				MEAN 452					
				STD 63					

Alumina, 3 mm x 4 mm, 3 pt, Current Fixture, ARE (Godfrey)



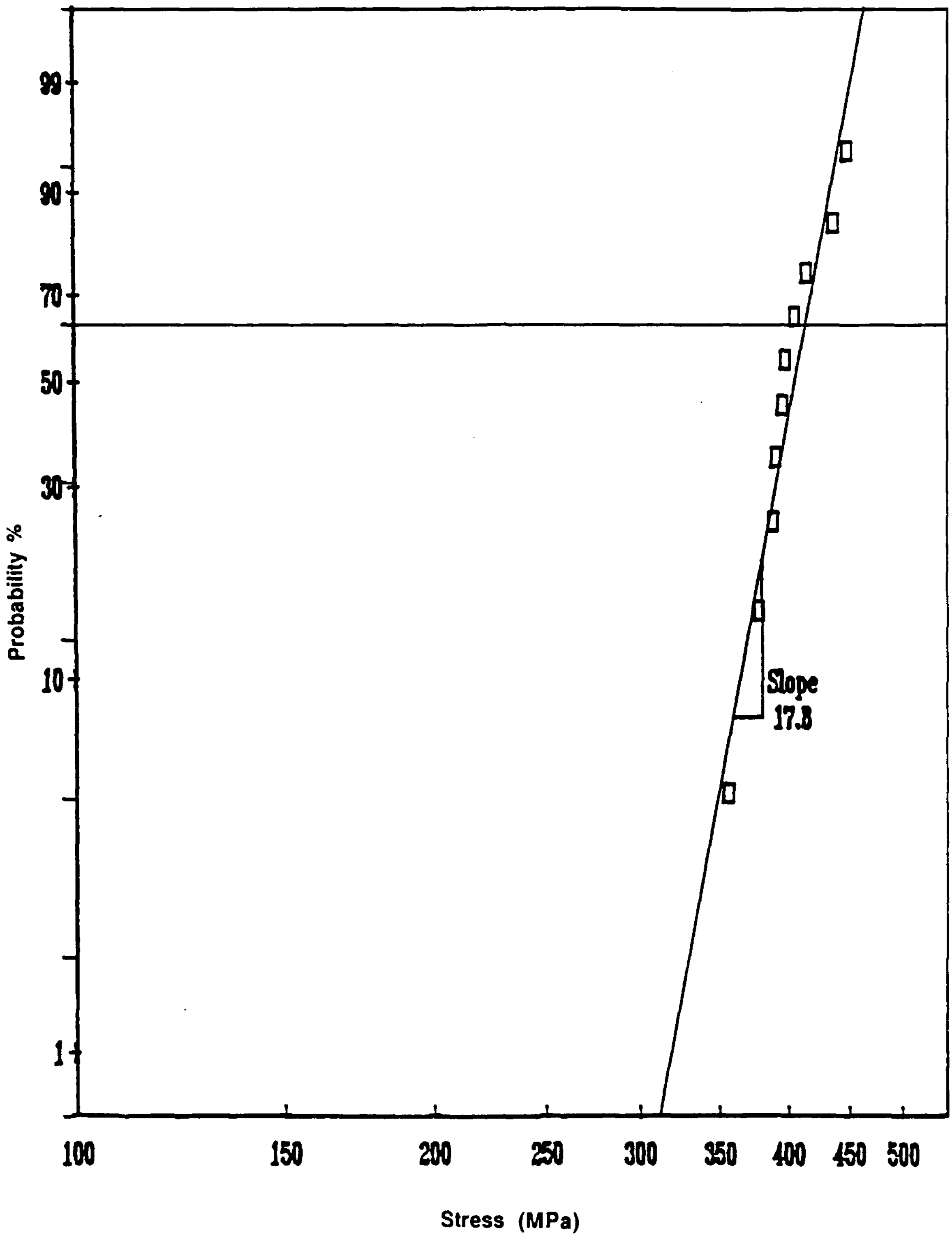
Alumina, 3 mm x 4 mm, 3 pt, MIL-STD-1942 (MR), ARE (Godfrey)

MATERIAL	AD-999	VINTAGE	
BILLET NO.		3 PT, MIL-STD B	
C.H SPEED	2.0 mm/min*	SPECIMEN SIZE	MIL-STD B, 3X4mm
TEMP		Characteristic Strength	
HUMIDITY		of B.B	412 MPA
TESTER		SLOPE	17.75
MOMENT ARM	20 mm	CHART SPEED	

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
1	N/A	4.0	3.0	356	51.6				
2	N/A	4.0	3.0	377	54.7				
3	N/A	4.0	3.0	388	56.2				
4	N/A	4.0	3.0	390	56.5				
5	N/A	4.0	3.0	395	57.2				
6	N/A	4.0	3.0	397	57.5				
7	N/A	4.0	3.0	404	58.5				
8	N/A	4.0	3.0	413	59.9				
9	N/A	4.0	3.0	435	63.1				
10	N/A	4.0	3.0	447	64.8				
				MEAN					
				400					
				STD					
				25					

*A wrong C.H. speed was used. It should have been 0.5 mm/min

Alumina, 3 mm x 4 mm, 3 pt, MTL-STD-1942 (MR), ARE (Godfrey)

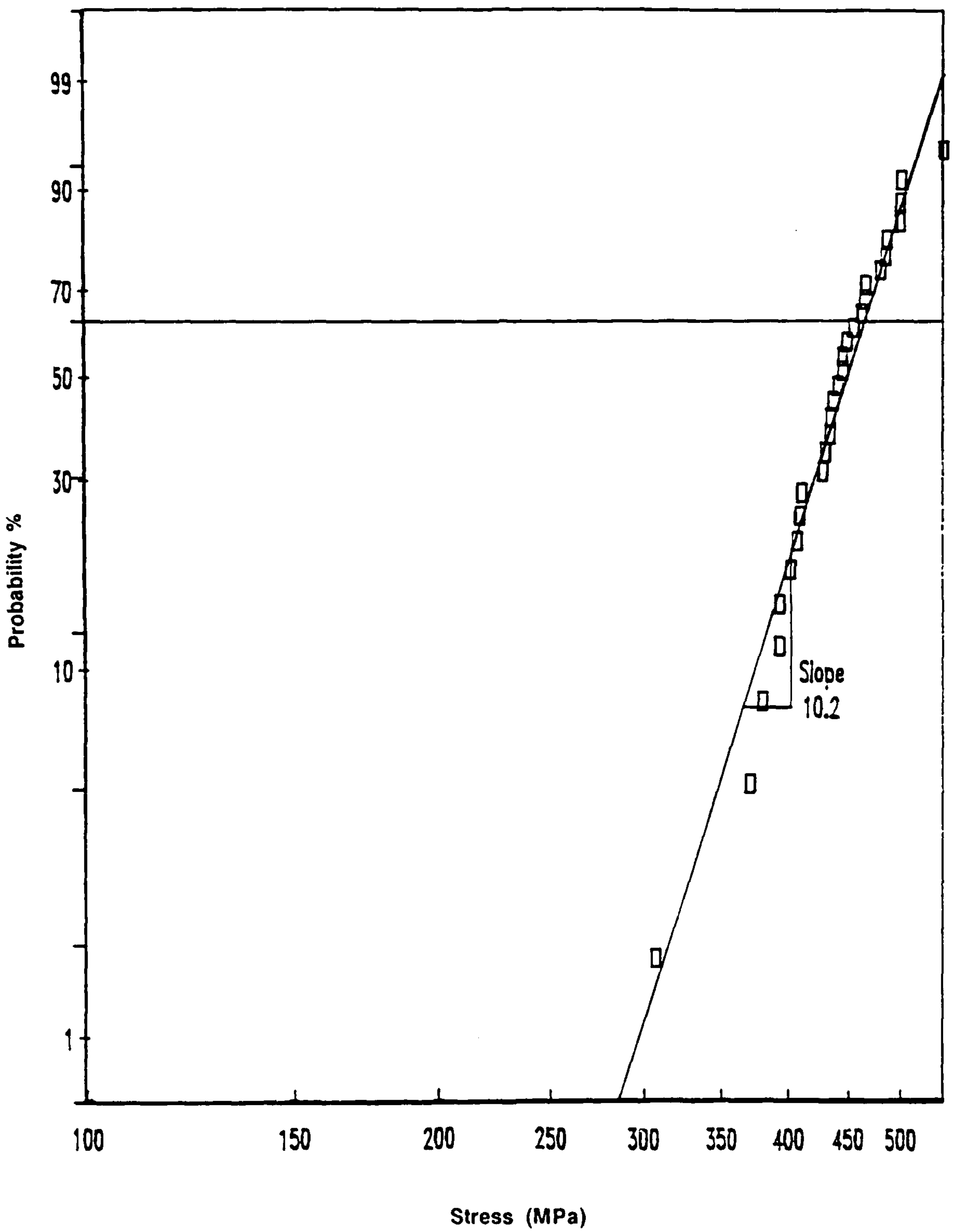


Alumina, 3 mm x 4 mm, 3 pt, MIL-STD-1942 (MR), MTL (Quinn)

MATERIAL	COORS AD-999	VINTAGE	1984 A1203
BILLET NO.		MIL-STD B, 3-POINT	
C.H SPEED	.5 mm/min	SPECIMEN SIZE	B
TEMP	83 F	Characteristic Strength	
HUMIDITY	26%	of B.B	466 MPA
TESTER	M. SLAVIN	SLOPE	10.20
MOMENT ARM	20 mm	CHART SPEED	100 mm/min

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
38	183.0	3.998	2.990	307	44.6		NO	NO	
55	223.0	3.995	3.005	371	53.8		NO	NO	
396	229.0	3.995	3.010	380	55.1		NO	NO	
441	234.0	4.001	2.990	393	56.9		NO	NO	
22	236.0	4.023	2.992	393	57.0		NO	NO	
339	242.0	4.028	2.995	402	58.3		NO	NO	
254	245.0	4.001	3.005	407	59.0		NO	NO	
167	243.0	3.995	2.987	409	59.3		NO	NO	
147	246.0	4.013	2.992	411	59.6		NO	NO	
87	256.0	4.006	2.992	428	62.1		NO	NO	
190	259.0	4.001	3.005	430	62.4		NO	NO	
109	259.0	4.003	2.990	434	63.0		NO	NO	
151	263.0	4.016	3.007	435	63.0		NO	NO	
95	262.0	3.993	3.002	437	63.4		NO	NO	
382	262.0	4.001	2.985	441	64.0		NO	NO	
260	268.0	4.016	3.000	445	64.5		NO	NO	
42	265.0	3.995	2.990	445	64.6		NO	NO	
345	271.0	4.013	3.005	449	65.1		NO	NO	
426	276.0	3.998	3.018	455	66.0		NO	NO	
255	277.0	3.995	3.002	462	67.0		NO	NO	
58	278.0	3.995	2.997	465	67.4		NO	NO	
438	280.0	4.008	3.000	466	67.5		NO	NO	
181	288.0	4.013	2.995	480	69.6		NO	NO	
326	292.0	4.011	3.000	485	70.4		NO	NO	
16	291.0	3.998	2.997	486	70.5		NO	NO	
138	299.0	3.990	3.002	499	72.4		NO	NO	
232	298.0	4.001	2.992	499	72.4		NO	NO	
241	300.0	3.998	3.000	500	72.6		NO	NO	
420	326.0	4.026	2.990	543	78.8		NO	NO	
143	340.0	4.011	3.007	562	81.6		NO	NO	
				MEAN 444					
				STD 51					

Alumina, 3 mm x 4 mm, 3 pt, MIL-STD-1942 (MR), MTL (Quinn)

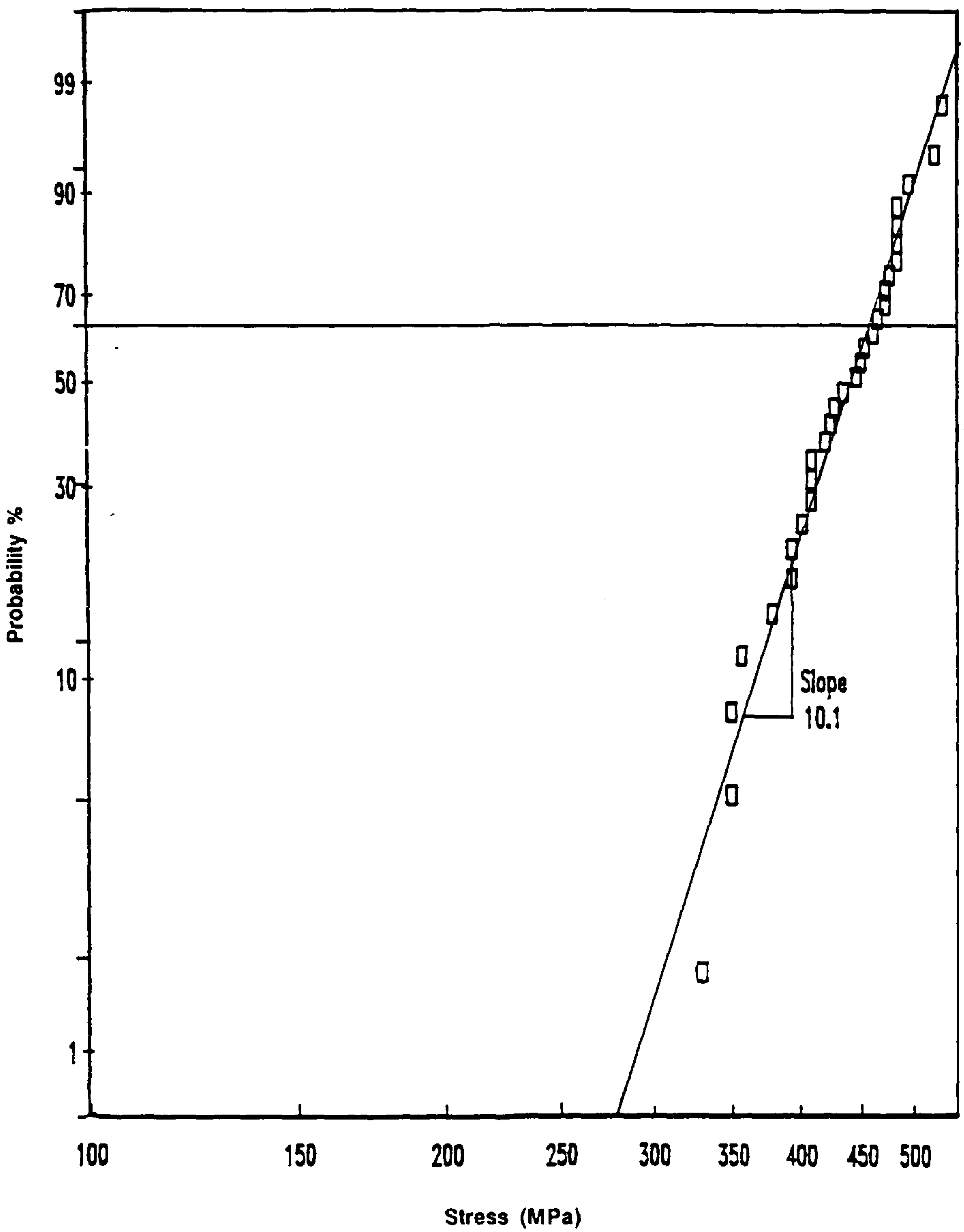


Alumina, 3 mm x 4 mm, 3 pt, MIL-STD-1942 (MR), ORF (Sullivan)

MATERIAL	COORS AD-999	VINTAGE	
BILLET NO.		3-POINT BEND	
C.H SPEED	.5mm/min	SPECIMEN SIZE	MIL-STD B (3X4mm)
TEMP	23.6 C	Characteristic Strength	
HUMIDITY	11.3 %	of B.B	456 MPA
TESTER	LAUZON/SULLIVAN	SLOPE	10.13
MOMENT ARM	20 mm	CHART SPEED	N/A

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
74	N/A	4.0	3.0	330	47.9		NO	NO	
156	N/A	4.0	3.0	349	50.6				
423	N/A	4.0	3.0	349	50.6				
290	N/A	4.0	3.0	356	51.6				
131	N/A	4.0	3.0	378	54.8				
133	N/A	4.0	3.0	393	57.0				
347	N/A	4.0	3.0	393	57.0				
187	N/A	4.0	3.0	401	58.2				
306	N/A	4.0	3.0	408	59.2				
122	N/A	4.0	3.0	408	59.2				
31	N/A	4.0	3.0	408	59.2				
273	N/A	4.0	3.0	419	60.8				
308	N/A	4.0	3.0	423	61.4				
82	N/A	4.0	3.0	426	61.8				
352	N/A	4.0	3.0	434	62.9				
90	N/A	4.0	3.0	445	64.5				
251	N/A	4.0	3.0	449	65.1				
292	N/A	4.0	3.0	452	65.6				
46	N/A	4.0	3.0	460	66.7				
34	N/A	4.0	3.0	464	67.3				
3	N/A	4.0	3.0	471	68.3				
449	N/A	4.0	3.0	471	68.3				
242	N/A	4.0	3.0	475	68.9				
357	N/A	4.0	3.0	482	69.9				
372	N/A	4.0	3.0	482	69.9				
442	N/A	4.0	3.0	482	69.9				
435	N/A	4.0	3.0	482	69.9				
125	N/A	4.0	3.0	493	71.5				
446	N/A	4.0	3.0	519	75.3				
173	N/A	4.0	3.0	527	76.4				
				MEAN 434					
				STD 51					

Alumina, 3 mm x 4 mm, 3 pt, MIL-STD-1942 (MR), ORF (Sullivan)

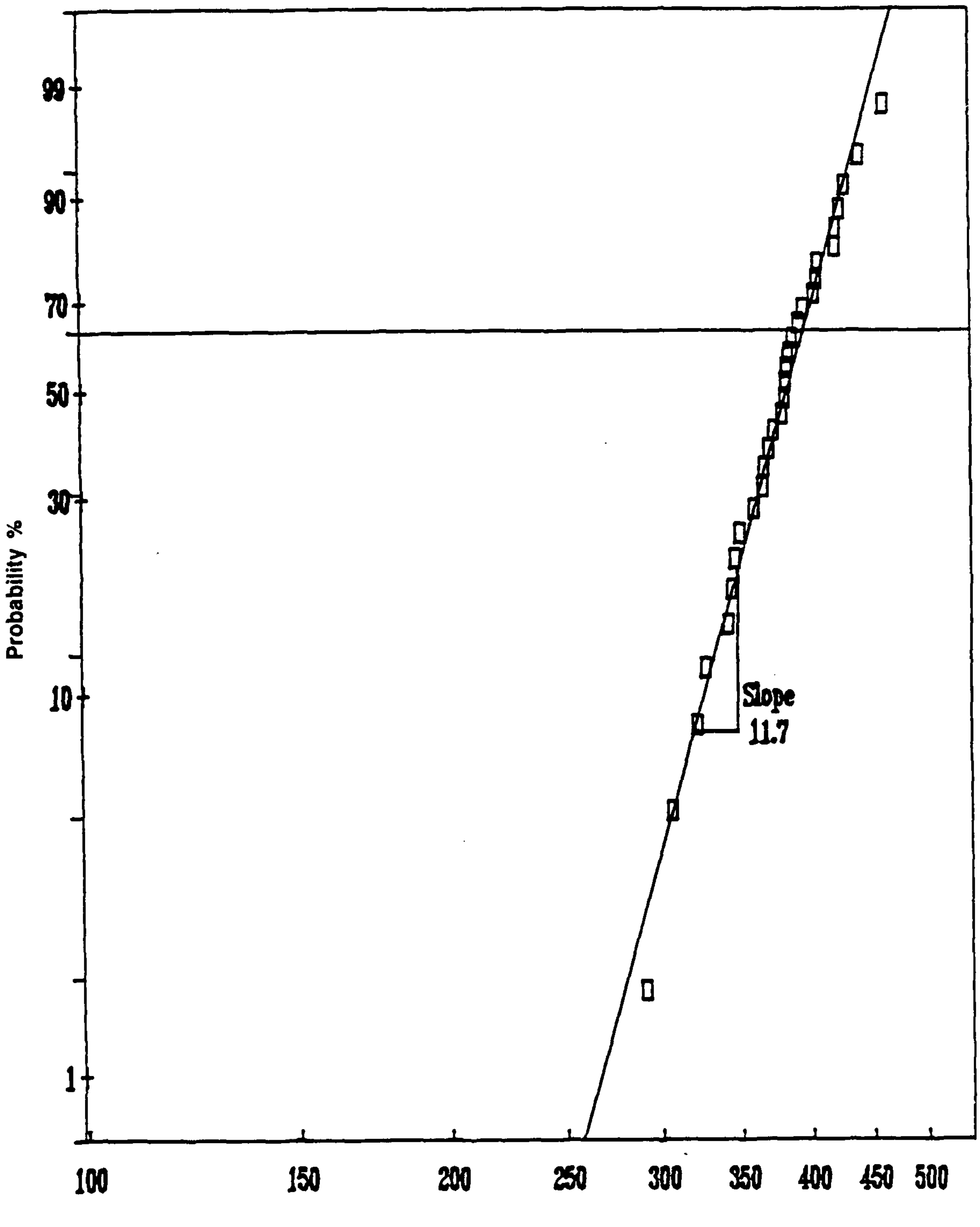


Alumina, 3 mm x 4 mm, 4 pt, Current Fixture, ARE (Godfrey)

MATERIAL	AD-999	VINTAGE	
BILLET NO.		4 PT, ARE FIXTURE	
C.H SPEED	2.0 mm/min	SPECIMEN SIZE	MIL-STD B, 3X4mm
TEMP		Characteristic Strength	
HUMIDITY		of B.B	395 MPA
TESTER		SLOPE	11.70
MOMENT ARM	10.475 mm	CHART SPEED	

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
1	N/A	4.0	3.0	291	42.2				
2	N/A	4.0	3.0	306	44.4				
3	N/A	4.0	3.0	322	46.7				
4	N/A	4.0	3.0	327	47.4				
5	N/A	4.0	3.0	342	49.5				
6	N/A	4.0	3.0	344	49.9				
7	N/A	4.0	3.0	347	50.2				
8	N/A	4.0	3.0	350	50.7				
9	N/A	4.0	3.0	359	52.0				
10	N/A	4.0	3.0	366	53.0				
11	N/A	4.0	3.0	366	53.1				
12	N/A	4.0	3.0	370	53.6				
13	N/A	4.0	3.0	373	54.1				
14	N/A	4.0	3.0	379	54.9				
15	N/A	4.0	3.0	381	55.2				
16	N/A	4.0	3.0	382	55.3				
17	N/A	4.0	3.0	383	55.4				
18	N/A	4.0	3.0	384	55.7				
19	N/A	4.0	3.0	387	56.0				
20	N/A	4.0	3.0	391	56.7				
21	N/A	4.0	3.0	395	57.2				
22	N/A	4.0	3.0	403	58.4				
23	N/A	4.0	3.0	405	58.7				
24	N/A	4.0	3.0	406	58.8				
25	N/A	4.0	3.0	420	60.8				
26	N/A	4.0	3.0	420	60.9				
27	N/A	4.0	3.0	424	61.4				
28	N/A	4.0	3.0	428	62.0				
29	N/A	4.0	3.0	440	63.7				
30	N/A	4.0	3.0	462	66.9				
				MEAN					
				378					
				STD					
				39					

Alumina, 3 mm x 4 mm, 4 pt, Current Fixture, ARE (Godfrey)

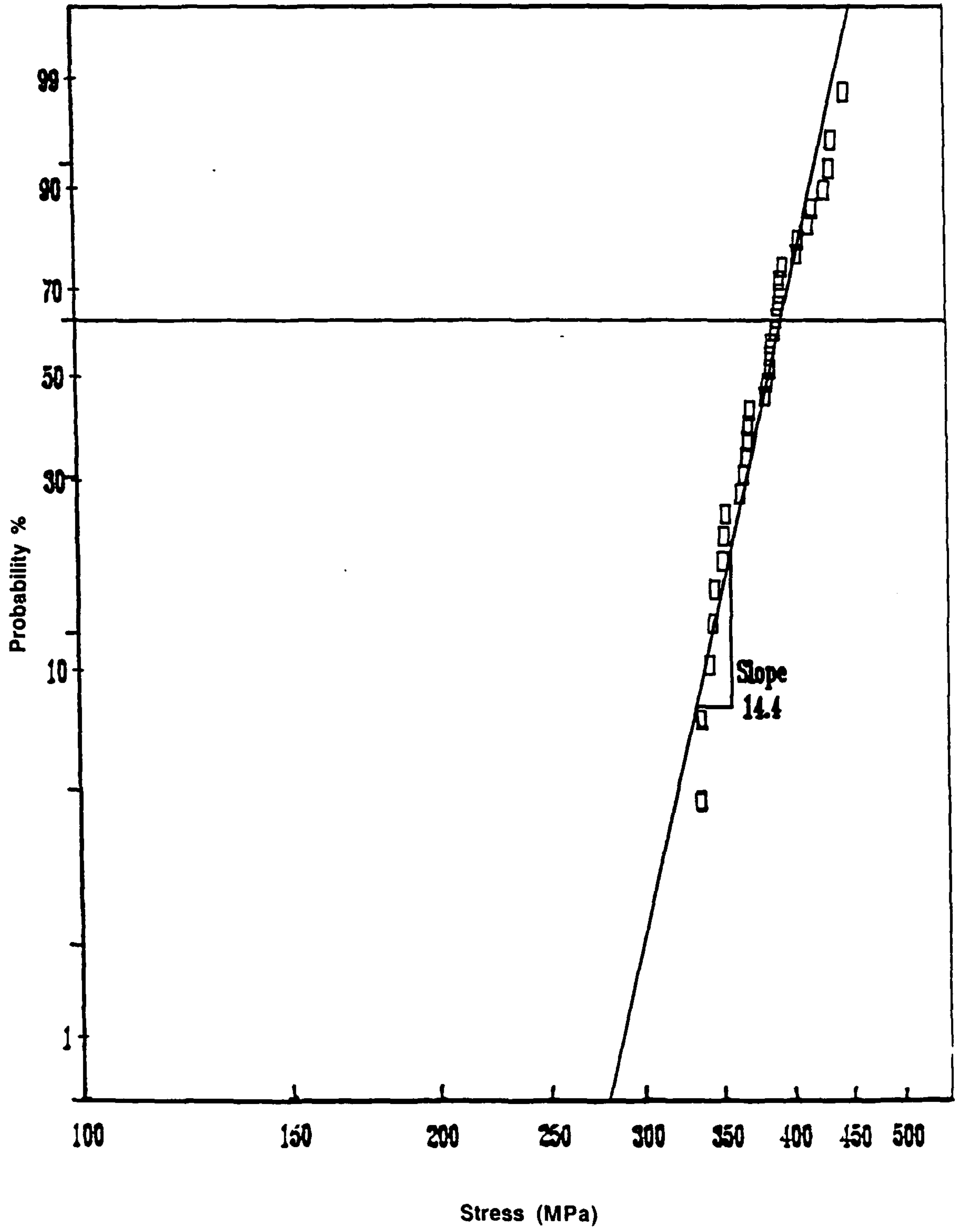


Alumina, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), IITRI

MATERIAL	AD-999	VINTAGE	
BILLET NO.		MIL-STD B	
C.H SPEED		SPECIMEN SIZE	MIL-STD B (AL2F1-35)
TEMP		Characteristic Strength	
HUMIDITY		of B.B	395 MPA
TESTER		SLOPE	14.43
MOMENT ARM	10 mm	CHART SPEED	

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
34	N/A	4.0	3.0	320	46.4				
31	N/A	4.0	3.0	334	48.5				
19	N/A	4.0	3.0	335	48.6				
28	N/A	4.0	3.0	341	49.5				
25	N/A	4.0	3.0	343	49.8				
26	N/A	4.0	3.0	345	50.0				
7	N/A	4.0	3.0	350	50.7				
10	N/A	4.0	3.0	351	50.9				
32	N/A	4.0	3.0	352	51.1				
9	N/A	4.0	3.0	363	52.6				
3	N/A	4.0	3.0	365	53.0				
21	N/A	4.0	3.0	367	53.2				
24	N/A	4.0	3.0	368	53.3				
16	N/A	4.0	3.0	369	53.5				
22	N/A	4.0	3.0	370	53.7				
23	N/A	4.0	3.0	381	55.3				
2	N/A	4.0	3.0	383	55.6				
8	N/A	4.0	3.0	385	55.9				
14	N/A	4.0	3.0	385	55.9				
13	N/A	4.0	3.0	386	55.9				
18	N/A	4.0	3.0	389	56.4				
27	N/A	4.0	3.0	391	56.6				
6	N/A	4.0	3.0	392	56.8				
15	N/A	4.0	3.0	393	56.9				
5	N/A	4.0	3.0	393	57.0				
20	N/A	4.0	3.0	395	57.3				
29	N/A	4.0	3.0	406	59.0				
11	N/A	4.0	3.0	408	59.2				
30	N/A	4.0	3.0	417	60.4				
17	N/A	4.0	3.0	420	60.9				
33	N/A	4.0	3.0	430	62.4				
35	N/A	4.0	3.0	434	62.9				
12	N/A	4.0	3.0	436	63.2				
4	N/A	4.0	3.0	447	64.9				
				MEAN					
				381					
				STD					
				31.5					

Alumina, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), IITRI

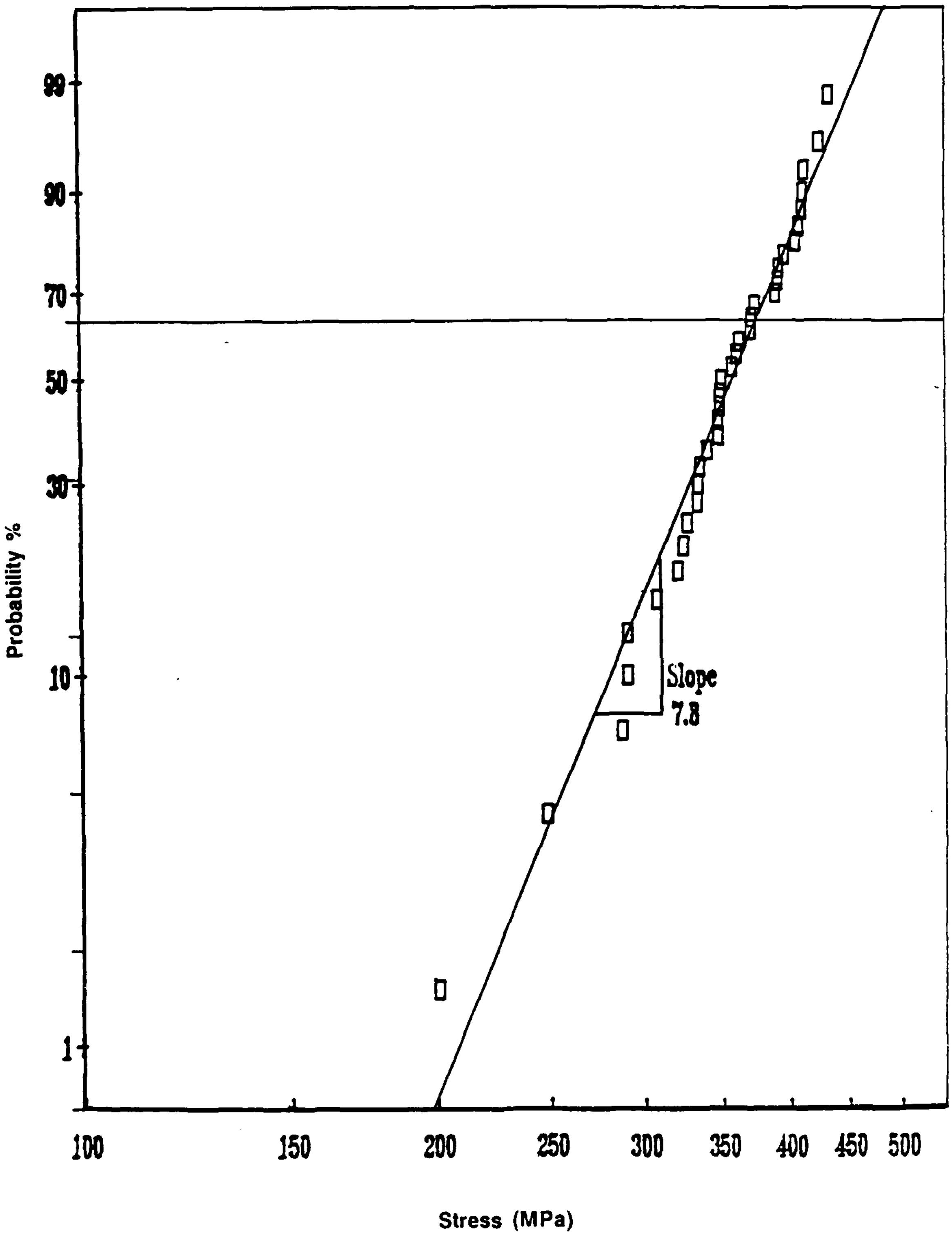


Alumina, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), MRL (Johnston)

MATERIAL	AD-999	VINTAGE	
BILLET NO.		4 PT BENDING, MIL STD B	
C.H SPEED	.5 MM/MIN	SPECIMEN SIZE	MIL STB B
TEMP	20 C	Characteristic Strength	
HUMIDITY	54 %	of B.B	376 MPA
TESTER		SLOPE	7.834
MOMENT ARM	10 mm	CHART SPEED	

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
60	240.5	3.999	2.999	201	29.1		NO	NO	
213	299.0	4.000	3.001	249	36.1		NO	NO	
196	345.0	3.998	3.000	288	41.7		NO	NO	
111	350.0	4.010	3.000	291	42.2		NO	NO	
410	353.5	3.992	3.021	291	42.2		NO	NO	
279	369.5	4.008	2.995	308	44.7		NO	NO	
129	384.5	4.003	2.996	321	46.6		NO	NO	
226	385.5	3.976	2.994	324	47.1		NO	NO	
393	392.5	4.024	2.991	327	47.4		NO	NO	
402	406.5	3.997	3.024	334	48.4		NO	NO	
228	400.5	3.991	3.002	334	48.5		NO	NO	
425	399.0	3.995	2.990	335	48.6		NO	NO	
433	402.5	3.998	2.981	340	49.3		NO	NO	
5	415.5	4.010	2.989	348	50.5		NO	NO	
363	421.0	4.017	3.005	348	50.5		NO	NO	
229	420.0	4.013	2.999	349	50.6		NO	NO	
392	422.5	4.010	3.008	349	50.7		NO	NO	
249	420.0	4.000	3.000	350	50.8		NO	NO	
264	430.0	4.016	2.996	358	51.9		NO	NO	
216	431.5	3.984	3.000	361	52.4		NO	NO	
427	435.5	4.000	2.999	363	52.7		NO	NO	
380	445.0	4.025	2.987	372	53.9		NO	NO	
269	447.5	4.001	3.004	372	53.9		NO	NO	
136	446.0	3.979	2.997	374	54.3		NO	NO	
50	466.0	3.991	2.998	390	56.5		NO	NO	
386	476.0	4.000	3.019	392	56.8		NO	NO	
33	471.0	4.000	3.001	392	56.9		NO	NO	
161	474.5	3.997	2.996	397	57.5		NO	NO	
144	486.0	4.002	2.996	406	58.9		NO	NO	
198	490.0	4.021	2.992	408	59.2		NO	NO	
268	493.0	4.012	2.994	411	59.6		NO	NO	
75	493.5	3.999	2.998	412	59.7		NO	NO	
135	495.0	3.994	3.001	413	59.9		NO	NO	
390	512.5	4.028	2.995	426	61.7		NO	NO	
205	522.5	4.010	3.002	434	62.9		NO	NO	
				MEAN					
				353.					
				STD					
				50.0					

Alumina, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), MRL (Johnston)



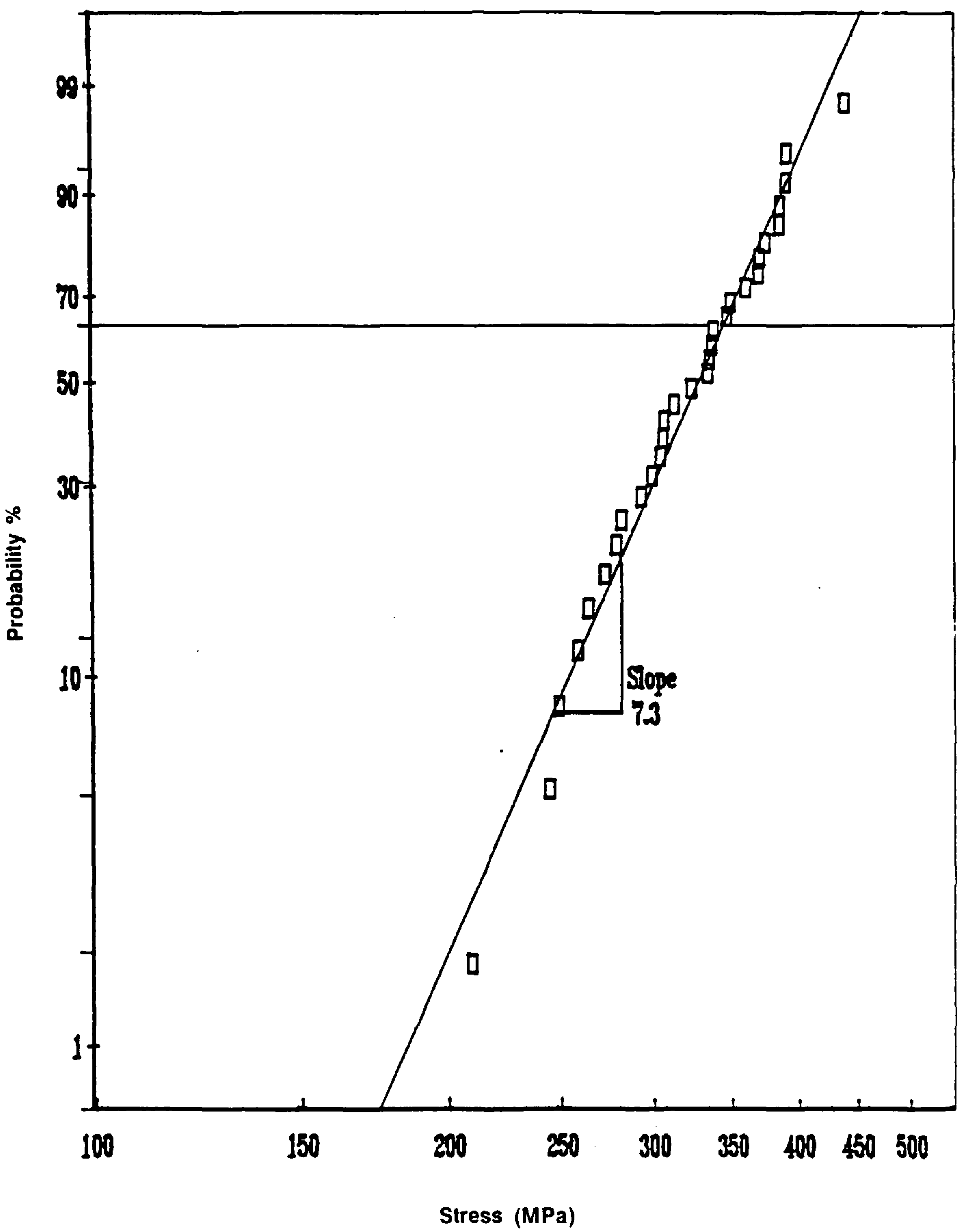
Alumina, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), ARE (Godfrey)

MATERIAL	AD-999	VINTAGE	
BILLET NO.		4 PT, MIL-STD B	
C.H SPEED	2.0 mm/min*	SPECIMEN SIZE	MIL-STD B, 3X4mm
TEMP		Characteristic Strength	
HUMIDITY		of B.B	345 MPA
TESTER		SLOPE	7.344
MOMENT ARM	10 mm	CHART SPEED	

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
1	N/A	4.0	3.0	209	30.3				
2	N/A	4.0	3.0	244	35.4				
3	N/A	4.0	3.0	249	36.0				
4	N/A	4.0	3.0	258	37.4				
5	N/A	4.0	3.0	264	38.2				
6	N/A	4.0	3.0	272	39.5				
7	N/A	4.0	3.0	279	40.4				
8	N/A	4.0	3.0	282	40.8				
9	N/A	4.0	3.0	293	42.4				
10	N/A	4.0	3.0	299	43.4				
11	N/A	4.0	3.0	304	44.1				
12	N/A	4.0	3.0	306	44.3				
13	N/A	4.0	3.0	306	44.4				
14	N/A	4.0	3.0	312	45.3				
15	N/A	4.0	3.0	323	46.8				
16	N/A	4.0	3.0	334	48.3				
17	N/A	4.0	3.0	335	48.5				
18	N/A	4.0	3.0	336	48.7				
19	N/A	4.0	3.0	337	48.9				
20	N/A	4.0	3.0	347	50.2				
21	N/A	4.0	3.0	349	50.6				
22	N/A	4.0	3.0	360	52.2				
23	N/A	4.0	3.0	370	53.5				
24	N/A	4.0	3.0	370	53.6				
25	N/A	4.0	3.0	374	54.3				
26	N/A	4.0	3.0	385	55.8				
27	N/A	4.0	3.0	385	55.8				
28	N/A	4.0	3.0	389	56.4				
29	N/A	4.0	3.0	390	56.5				
30	N/A	4.0	3.0	438	63.5				
				MEAN					
				323.					
				STD					
				52.0					

*The wrong crosshead rate was used. It should have been 0.5 mm/min.

Alumina, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), ARE (Godfrey)

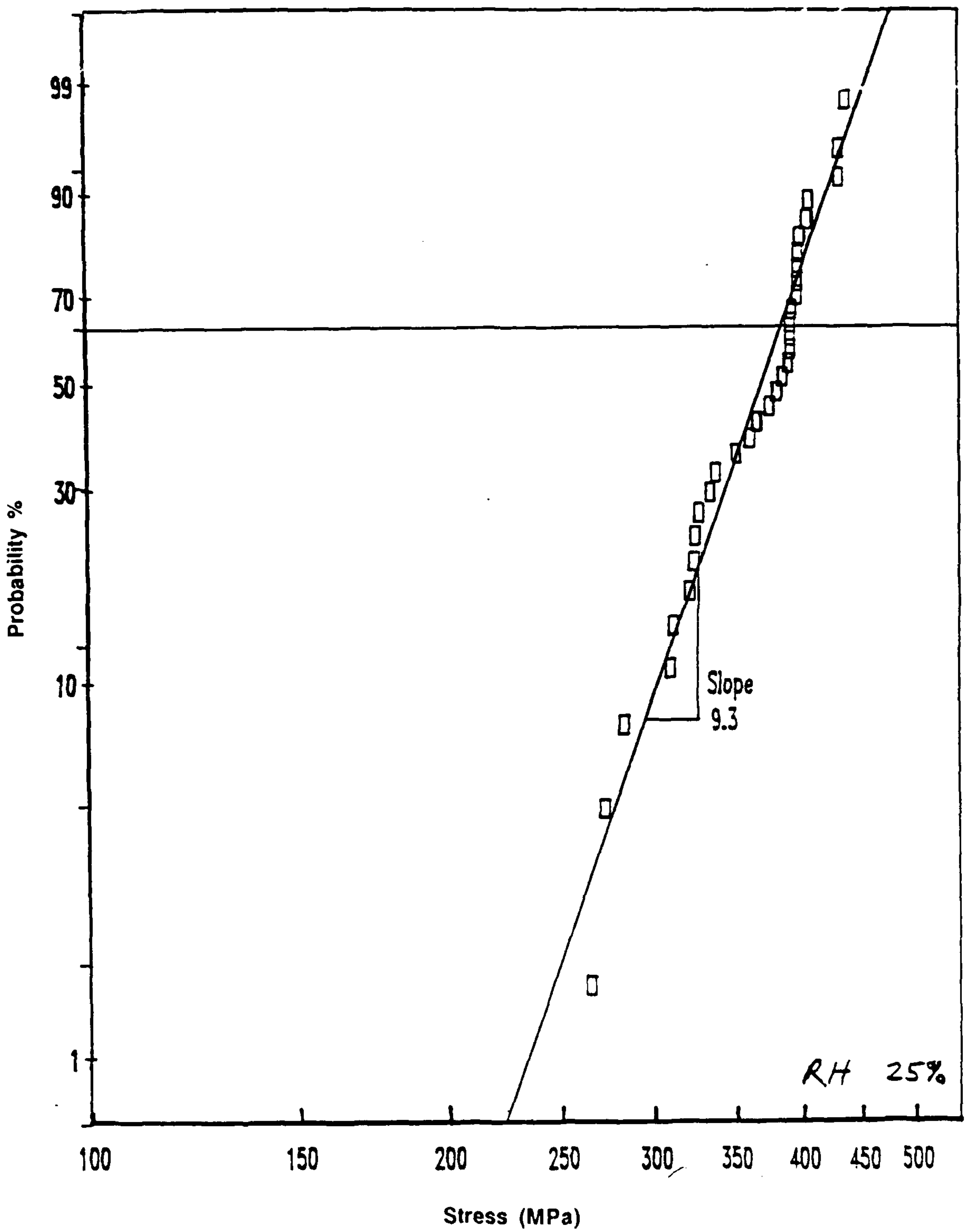


Alumina, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), ARE (Quinn)

MATERIAL	COORS AD-999	VINTAGE	
BILLET NO.		FOUR POINT BEND	
C.H SPEED	0.5 mm/min	SPECIMEN SIZE	B
TEMP	79°	Characteristic Strength	
HUMIDITY	25%	of B.B	384 MPA
TESTER	S. WESTELMAN	SLOPE	9.257
MOMENT ARM	10 mm	CHART SPEED	100

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
119	316.5	4.004	2.994	265	38.4		NO	NO	
371	325.0	4.000	2.996	272	39.4		NO	NO	
215	340.0	4.000	3.004	283	41.0		NO	NO	
276	371.5	4.014	2.996	309	44.9		NO	NO	
343	374.0	4.028	2.994	311	45.1		NO	NO	
297	386.0	4.028	2.996	320	46.5		NO	NO	
384	388.0	4.000	3.000	323	46.9		NO	NO	
239	390.0	4.000	3.004	324	47.0		NO	NO	
176	391.0	4.012	2.994	326	47.3		NO	NO	
220	403.0	4.016	3.004	334	48.4		NO	NO	
189	403.5	3.998	2.998	337	48.9		NO	NO	
160	422.5	4.014	3.000	351	50.9		NO	NO	
63	435.0	4.014	3.002	361	52.3		NO	NO	
360	431.5	4.026	2.964	366	53.1		NO	NO	
266	449.5	4.014	2.994	375	54.4		NO	NO	
293	456.5	4.028	2.992	380	55.1		NO	NO	
320	465.0	4.014	3.008	384	55.7		NO	NO	
81	465.5	4.006	2.995	389	56.4		NO	NO	
13	465.5	4.018	2.984	390	56.6		NO	NO	
178	470.5	4.028	2.996	390	56.6		NO	NO	
141	467.5	4.004	2.994	391	56.7		NO	NO	
79	472.0	4.038	2.992	392	56.8		NO	NO	
93	475.0	3.996	3.002	396	57.4		NO	NO	
430	474.5	3.994	3.000	396	57.4		NO	NO	
92	477.0	4.004	3.004	396	57.4		NO	NO	
66	475.0	4.000	2.998	396	57.5		NO	NO	
317	479.0	4.028	2.994	398	57.7		NO	NO	
318	484.0	4.024	2.992	403	58.5		NO	NO	
383	487.5	4.020	2.999	404	58.7		NO	NO	
158	514.0	4.000	2.996	429	62.3		NO	NO	
221	513.5	4.000	2.994	430	62.3		NO	NO	
148	523.0	4.004	3.000	435	63.1		NO	NO	
				MEAN					
				364					
				STD					
				45					

Alumina, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), ARE (Quinn)

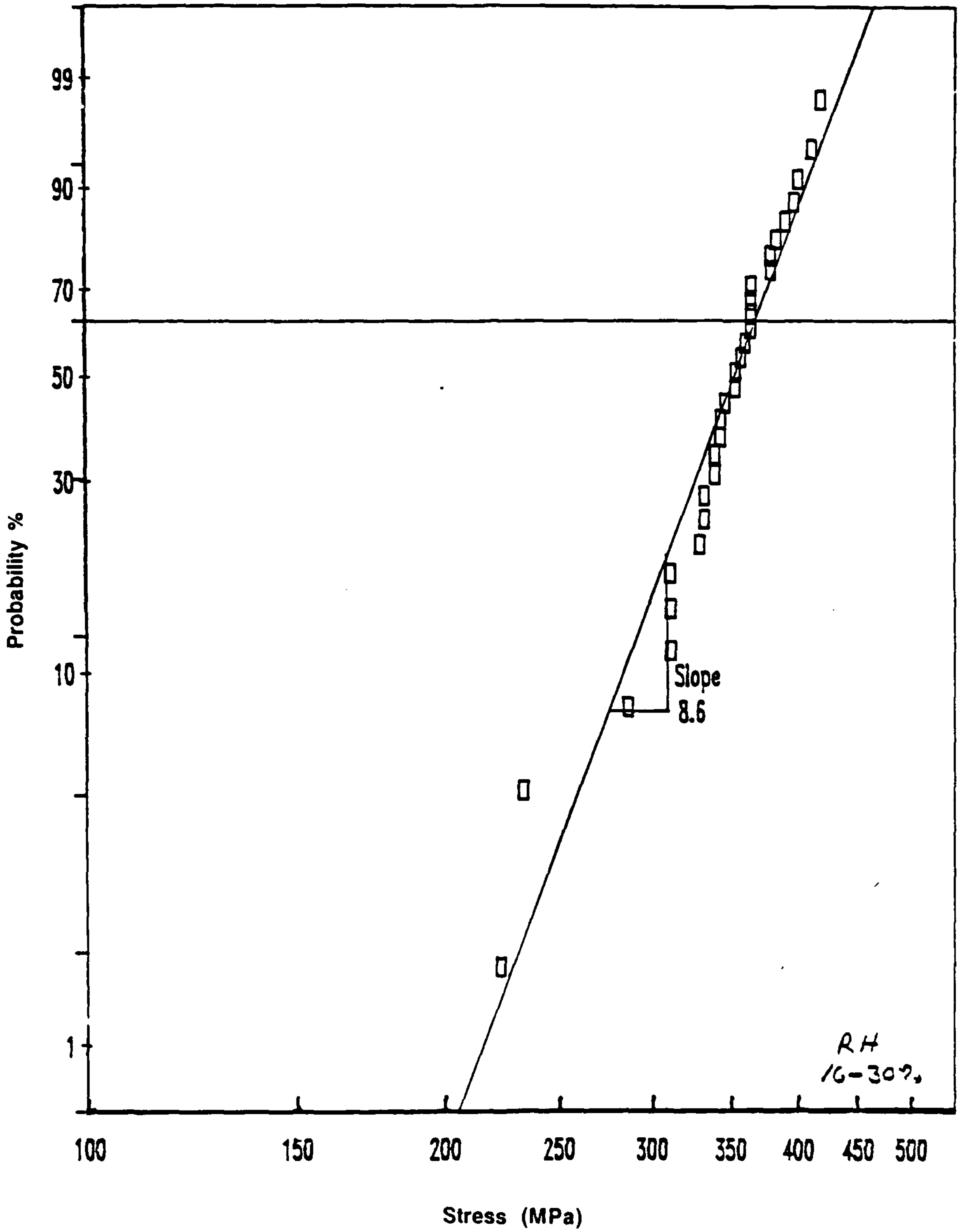


Alumina, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), ORF (Sullivan)

MATERIAL	COORS AD-999	VINTAGE	
BILLET NO.		1/4-POINT BEND	
C.H SPEED	.5mm/min	SPECIMEN SIZE	MIL-STD B (3X4mm)
TEMP	25.5 C / 24.3 C	Characteristic Strength	
HUMIDITY	55.9%/30.7%	of B.B	367 MPA
TESTER	LAUZON/SULLIVAN	SLOPE	8.606
MOMENT ARM	10 mm	CHART SPEED	N/A

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
149	N/A	4.0	3.0	223	32.3		NO	NO	
230	N/A	4.0	3.0	233	33.8				
59	N/A	4.0	3.0	286	41.5				
37	N/A	4.0	3.0	311	45.1				
416	N/A	4.0	3.0	311	45.1				
321	N/A	4.0	3.0	311	45.1				
319	N/A	4.0	3.0	329	47.7				
422	N/A	4.0	3.0	332	48.2				
14	N/A	4.0	3.0	332	48.2				
142	N/A	4.0	3.0	339	49.2				
193	N/A	4.0	3.0	339	49.2				
18	N/A	4.0	3.0	343	49.7				
336	N/A	4.0	3.0	343	49.7				
283	N/A	4.0	3.0	346	50.2				
12	N/A	4.0	3.0	353	51.2				
186	N/A	4.0	3.0	353	51.2				
234	N/A	4.0	3.0	357	51.8				
170	N/A	4.0	3.0	360	52.2				
1	N/A	4.0	3.0	364	52.8				
314	N/A	4.0	3.0	364	52.8				
56	N/A	4.0	3.0	364	52.8				
342	N/A	4.0	3.0	364	52.8				
366	N/A	4.0	3.0	378	54.8				
222	N/A	4.0	3.0	378	54.8				
263	N/A	4.0	3.0	382	55.4				
28	N/A	4.0	3.0	389	56.4				
203	N/A	4.0	3.0	396	57.4				
107	N/A	4.0	3.0	399	57.9				
267	N/A	4.0	3.0	410	59.5				
447	N/A	4.0	3.0	417	60.5				
				MEAN					
				347					
				STD					
				44					

Alumina, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), ORF (Sullivan)

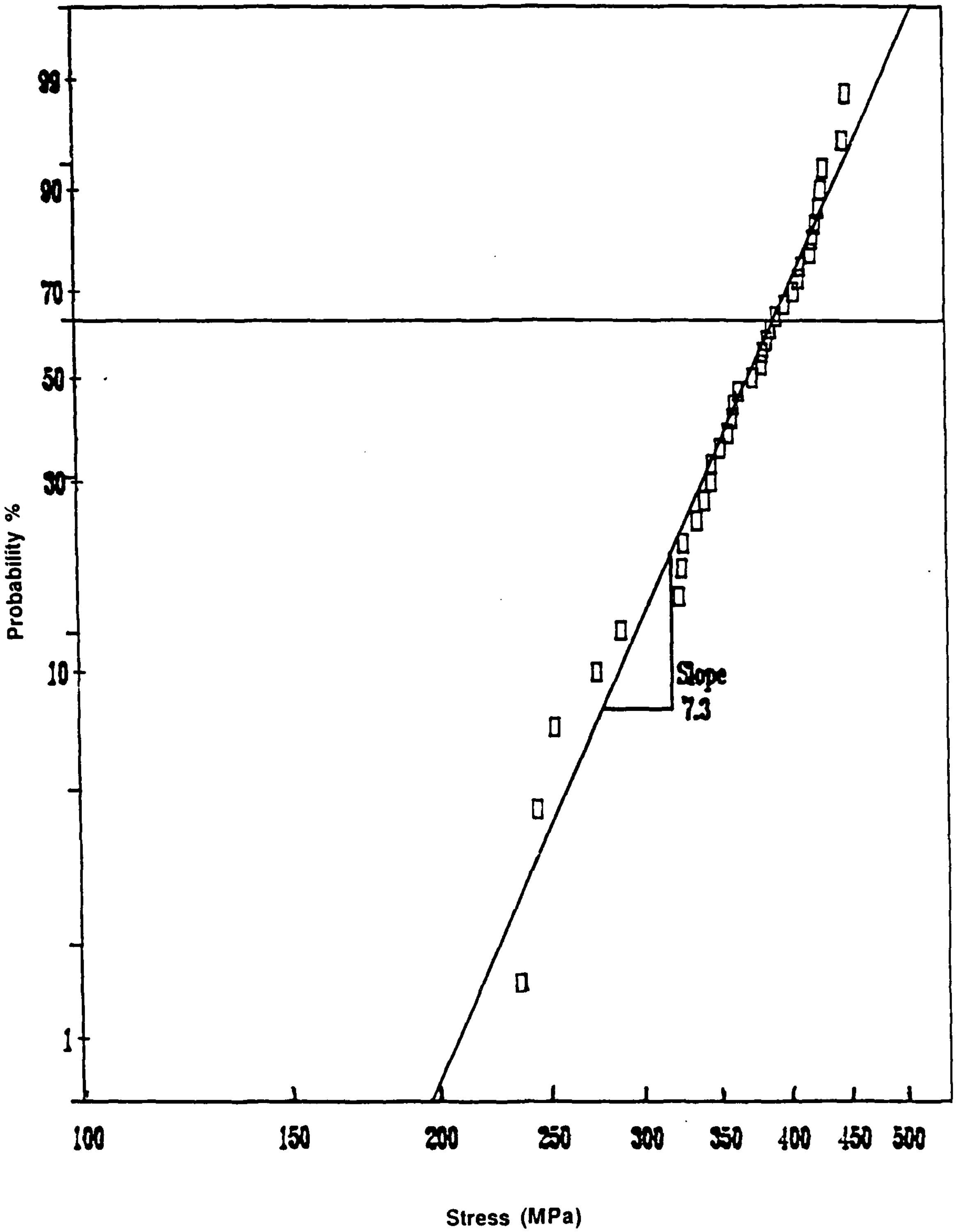


Alumina, 3 mm x 4 mm, 4 pt, Modified Fixture, IITRI

MATERIAL	AD-999	VINTAGE	
BILLET NO.		IITRI 20/40 mm	
C.H SPEED		SPECIMEN SIZE	MIL-STD B
TEMP		Characteristic Strength	
HUMIDITY		of B.B	389 MPA
TESTER		SLOPE	7.321
MOMENT ARM	10 mm	CHART SPEED	

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
25	N/A	4.0	3.0	235	34.1				
18	N/A	4.0	3.0	244	35.3				
32	N/A	4.0	3.0	252	36.6				
27	N/A	4.0	3.0	274	39.7				
11	N/A	4.0	3.0	287	41.7				
10	N/A	4.0	3.0	322	46.8				
13	N/A	4.0	3.0	324	47.0				
14	N/A	4.0	3.0	325	47.2				
24	N/A	4.0	3.0	334	48.5				
29	N/A	4.0	3.0	340	49.3				
20	N/A	4.0	3.0	344	49.9				
35	N/A	4.0	3.0	344	49.9				
12	N/A	4.0	3.0	350	50.8				
5	N/A	4.0	3.0	356	51.6				
16	N/A	4.0	3.0	359	52.1				
3	N/A	4.0	3.0	360	52.2				
28	N/A	4.0	3.0	364	52.8				
33	N/A	4.0	3.0	374	54.2				
8	N/A	4.0	3.0	380	55.2				
26	N/A	4.0	3.0	381	55.3				
9	N/A	4.0	3.0	384	55.7				
7	N/A	4.0	3.0	387	56.2				
2	N/A	4.0	3.0	392	56.8				
1	N/A	4.0	3.0	398	57.8				
19	N/A	4.0	3.0	405	58.7				
21	N/A	4.0	3.0	409	59.4				
30	N/A	4.0	3.0	411	59.6				
34	N/A	4.0	3.0	419	60.8				
15	N/A	4.0	3.0	421	61.0				
22	N/A	4.0	3.0	423	61.3				
6	N/A	4.0	3.0	426	61.8				
31	N/A	4.0	3.0	428	62.0				
17	N/A	4.0	3.0	429	62.3				
4	N/A	4.0	3.0	446	64.7				
23	N/A	4.0	3.0	449	65.1				
				MEAN					
				365					
				STD					
				56.1					

Alumina, 3 mm x 4 mm, 4 pt, Modified Fixture, IITRI

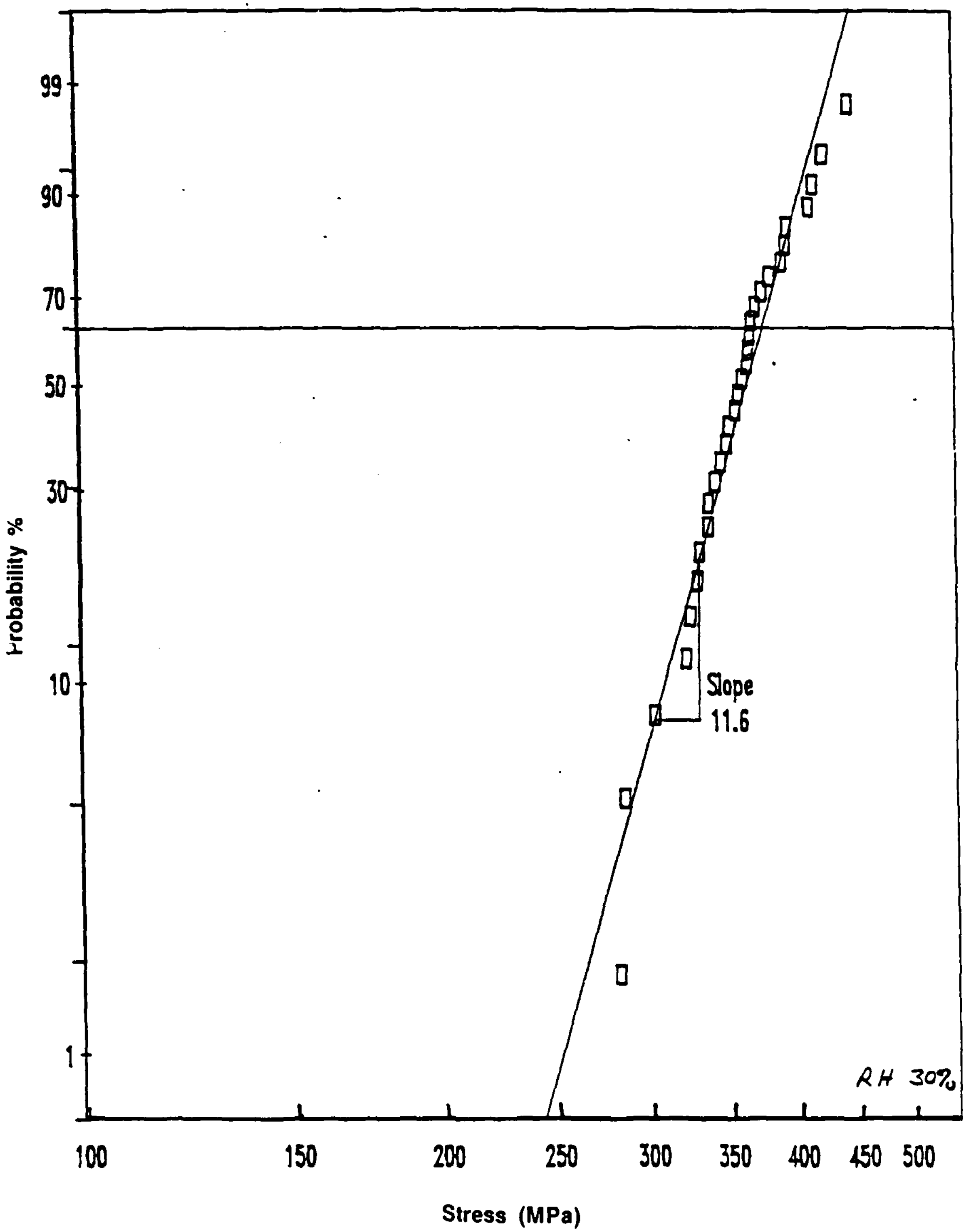


Alumina, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), NPL (Morrell)

MATERIAL	AD-999	VINTAGE	1985, LOT 2
BILLET NO.		1/4 POINT BEND	
C.H SPEED	.5 mm/min	SPECIMEN SIZE	MIL-STD B (3X4mm)
TEMP	23 C	Characteristic Strength	
HUMIDITY	30%	of B.B	375 MPA
TESTER		SLOPE	11.58
MOMENT ARM	10 mm	CHART SPEED	N/A

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
191	N/A	4.0	3.0	283	41.0		NO	NO	
452	N/A	4.0	3.0	286	41.5				
432	N/A	4.0	3.0	304	44.0				
280	N/A	4.0	3.0	322	46.8				
54	N/A	4.0	3.0	325	47.1				
405	N/A	4.0	3.0	329	47.7				
124	N/A	4.0	3.0	331	48.0				
258	N/A	4.0	3.0	337	48.8				
185	N/A	4.0	3.0	337	48.9				
358	N/A	4.0	3.0	341	49.5				
121	N/A	4.0	3.0	345	50.1				
334	N/A	4.0	3.0	350	50.7				
182	N/A	4.0	3.0	352	51.0				
298	N/A	4.0	3.0	356	51.6				
207	N/A	4.0	3.0	358	51.9				
137	N/A	4.0	3.0	360	52.3				
118	N/A	4.0	3.0	364	52.8				
249	N/A	4.0	3.0	365	52.9				
39	N/A	4.0	3.0	366	53.1				
378	N/A	4.0	3.0	367	53.3				
73	N/A	4.0	3.0	370	53.7				
25	N/A	4.0	3.0	375	54.4				
194	N/A	4.0	3.0	381	55.2				
265	N/A	4.0	3.0	389	56.5				
4	N/A	4.0	3.0	393	57.0				
367	N/A	4.0	3.0	393	57.1				
49	N/A	4.0	3.0	411	59.6				
224	N/A	4.0	3.0	415	60.1				
434	N/A	4.0	3.0	423	61.3				
11	N/A	4.0	3.0	443	64.3				
				MEAN 359					
				STD 37					

Alumina, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), NPL (Morrell)

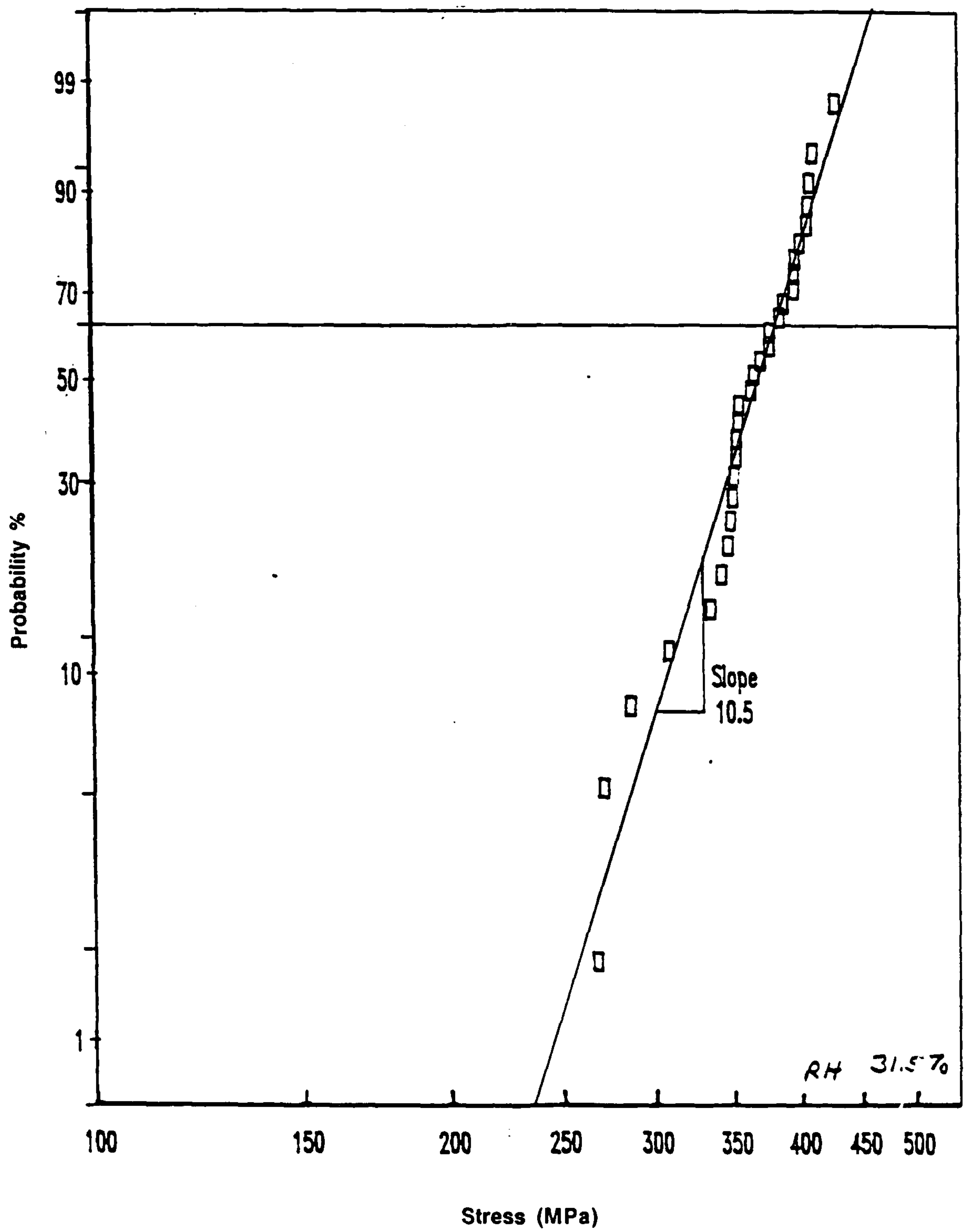


Alumina, 3 mm x 4 mm, 4 pt, Current Fixture, NPL (Morrell)

MATERIAL	AD-999	VINTAGE	1985, LOT 2
BILLET NO.		1/4 POINT BEND	
C.H SPEED	.5 mm/min	SPECIMEN SIZE	MIL-STD B (3X4)
TEMP	23 C	Characteristic Strength	
HUMIDITY	31.5%	of B.B	381 MPA
TESTER		SLOPE	10.45
MOMENT ARM	10 mm	CHART SPEED	N/A

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
261	N/A	4.0	3.0	268	38.9				
172	N/A	4.0	3.0	272	39.4				
412	N/A	4.0	3.0	286	41.5				
233	N/A	4.0	3.0	309	44.8				
218	N/A	4.0	3.0	335	48.6				
127	N/A	4.0	3.0	342	49.6				
244	N/A	4.0	3.0	347	50.3				
439	N/A	4.0	3.0	349	50.6				
444	N/A	4.0	3.0	350	50.8				
211	N/A	4.0	3.0	352	51.0				
401	N/A	4.0	3.0	353	51.2				
67	N/A	4.0	3.0	353	51.2				
399	N/A	4.0	3.0	354	51.4				
145	N/A	4.0	3.0	355	51.4				
303	N/A	4.0	3.0	364	52.7				
8	N/A	4.0	3.0	365	53.0				
328	N/A	4.0	3.0	370	53.7				
350	N/A	4.0	3.0	377	54.7				
192	N/A	4.0	3.0	377	54.7				
362	N/A	4.0	3.0	384	55.7				
84	N/A	4.0	3.0	387	56.2				
301	N/A	4.0	3.0	395	57.3				
146	N/A	4.0	3.0	396	57.4				
86	N/A	4.0	3.0	396	57.5				
155	N/A	4.0	3.0	400	58.0				
154	N/A	4.0	3.0	406	58.8				
209	N/A	4.0	3.0	406	59.0				
150	N/A	4.0	3.0	408	59.1				
349	N/A	4.0	3.0	410	59.5				
108	N/A	4.0	3.0	429	62.2				
				MEAN					
				363					
				STD					
				39					

Alumina, 3 mm x 4 mm, 4 pt, Current Fixture, NPL (Morrell)

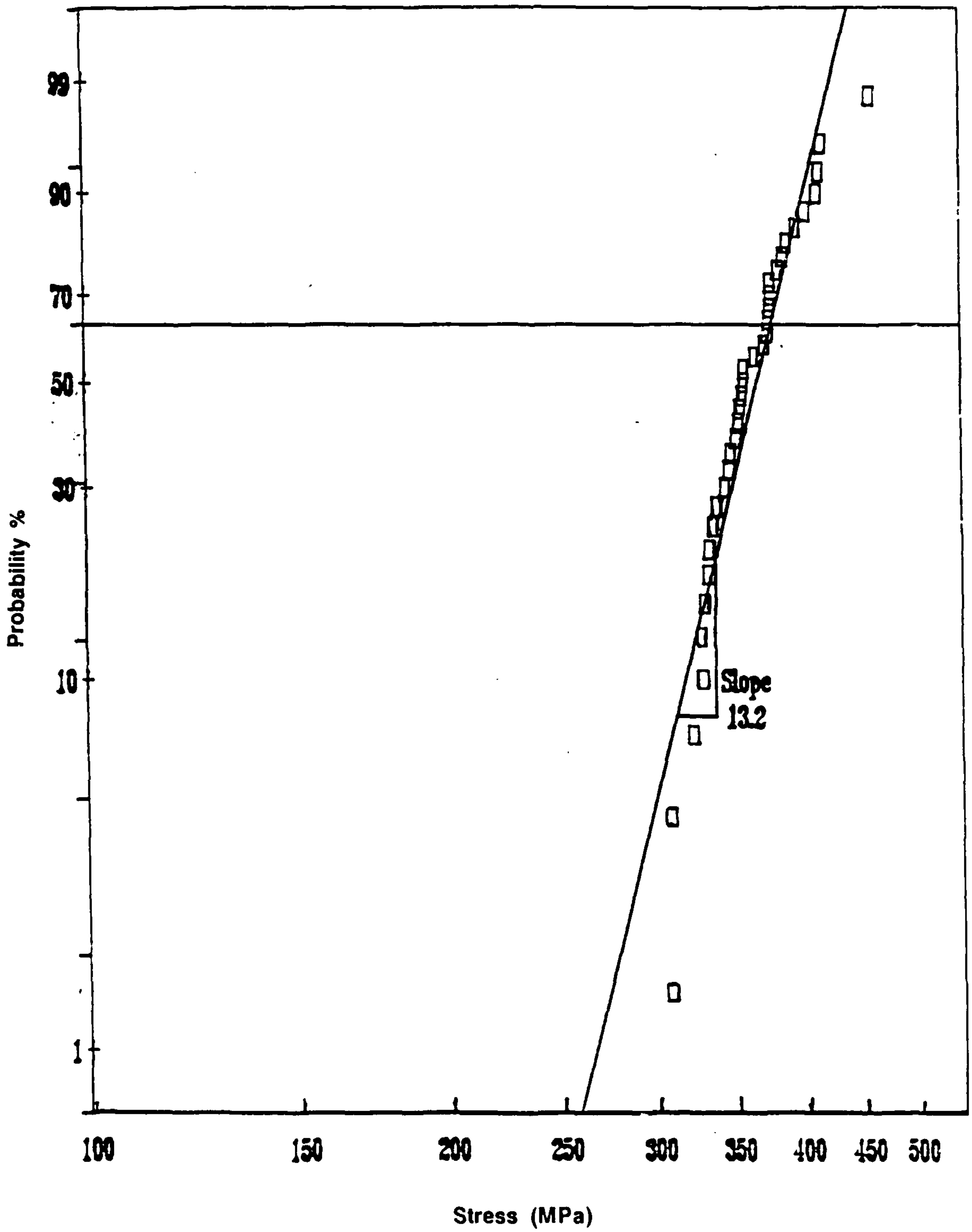


Alumina, 3 mm x 6 mm, 4 pt, MIL-STD-1942 (MR), IITRI

MATERIAL	AD-999	VINTAGE	
BILLET NO.		MIL-STD B	
C.H SPEED		SPECIMEN SIZE	3x6 mm
TEMP		Characteristic Strength	
HUMIDITY		of B.B	376 MPA
TESTER		SLOPE	13.20
MOMENT ARM	10 mm	CHART SPEED	

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
8	N/A	6.0	3.0	307	44.5				
26	N/A	6.0	3.0	308	44.7				
22	N/A	6.0	3.0	322	46.6				
28	N/A	6.0	3.0	328	47.6				
23	N/A	6.0	3.0	328	47.6				
18	N/A	6.0	3.0	329	47.7				
16	N/A	6.0	3.0	331	48.1				
29	N/A	6.0	3.0	332	48.1				
6	N/A	6.0	3.0	335	48.6				
33	N/A	6.0	3.0	337	48.9				
2	N/A	6.0	3.0	343	49.7				
4	N/A	6.0	3.0	345	50.0				
34	N/A	6.0	3.0	347	50.3				
24	N/A	6.0	3.0	350	50.8				
7	N/A	6.0	3.0	352	51.0				
31	N/A	6.0	3.0	353	51.2				
32	N/A	6.0	3.0	355	51.5				
21	N/A	6.0	3.0	356	51.7				
11	N/A	6.0	3.0	357	51.7				
30	N/A	6.0	3.0	364	52.8				
27	N/A	6.0	3.0	371	53.8				
9	N/A	6.0	3.0	373	54.2				
1	N/A	6.0	3.0	374	54.3				
14	N/A	6.0	3.0	375	54.4				
13	N/A	6.0	3.0	376	54.5				
25	N/A	6.0	3.0	376	54.5				
10	N/A	6.0	3.0	381	55.3				
5	N/A	6.0	3.0	385	55.9				
35	N/A	6.0	3.0	388	56.3				
19	N/A	6.0	3.0	395	57.3				
3	N/A	6.0	3.0	402	58.4				
12	N/A	6.0	3.0	411	59.6				
17	N/A	6.0	3.0	413	59.9				
20	N/A	6.0	3.0	415	60.3				
15	N/A	6.0	3.0	456	66.1				
				MEAN					
				362					
				STD					
				32.6					

Alumina, 3 mm x 6 mm, 4 pt, MIL-STD-1942 (MR), IITRI

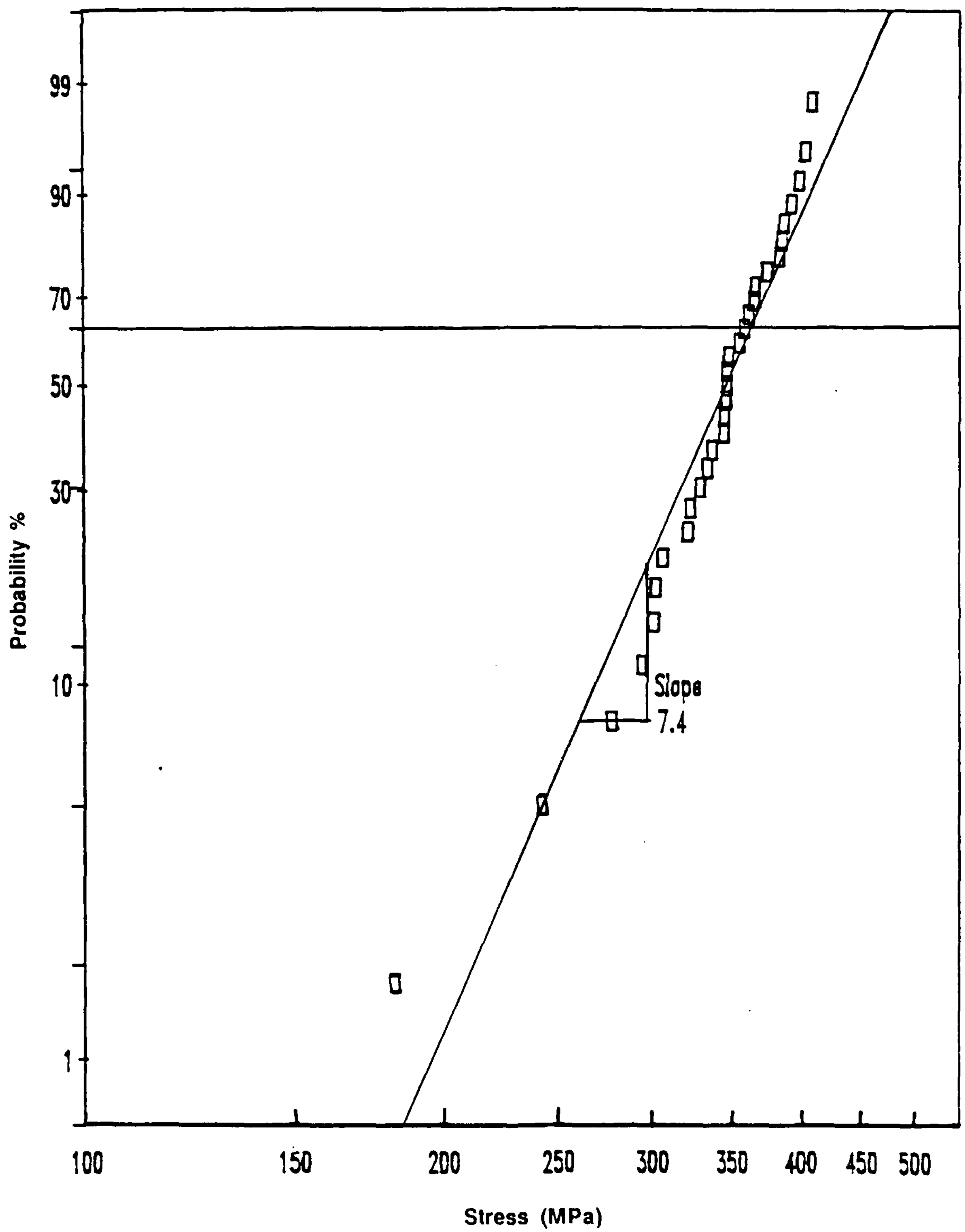


Alumina, 3 mm x 6 mm, 4 pt, MIL-STD-1942 (MR), MTL (Quinn)

MATERIAL	AD-999	VINTAGE	9/85, LOT2
BILLET NO.		MIL-STD B, 1/4 POINT	
C.H SPEED	.5 mm/min	SPECIMEN SIZE	B (3x6 mm)
TEMP	76 F	Characteristic Strength	
HUMIDITY	31%	of B.B	363 MPA
TESTER	S. WESTELMAN	SLOPE	7.412
MOMENT ARM	10 mm	CHART SPEED	100 mm/min

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
68	331.0	5.999	3.020	181	26.3		NO	NO	
122	440.0	6.017	3.012	242	35.1		NO	NO	
49	503.0	5.999	3.012	277	40.2		NO	NO	
156	536.0	6.007	3.020	294	42.6		NO	NO	
73	545.0	6.012	3.010	300	43.5		NO	NO	
116	551.0	6.005	3.023	301	43.7		NO	NO	
45	559.0	6.017	3.018	306	44.4		NO	NO	
83	582.0	6.010	3.010	321	46.5		NO	NO	
142	590.0	6.005	3.023	323	46.8		NO	NO	
23	601.0	6.002	3.023	329	47.7		NO	NO	
42	609.0	6.015	3.018	333	48.4		NO	NO	
105	616.0	6.005	3.023	337	48.8		NO	NO	
57	626.0	6.010	3.012	344	50.0		NO	NO	
130	628.0	6.015	3.015	345	50.0		NO	NO	
12	629.0	6.007	3.015	346	50.1		NO	NO	
162	628.0	5.999	3.012	346	50.2		NO	NO	
35	630.0	5.994	3.018	346	50.2		NO	NO	
77	632.0	6.010	3.012	348	50.4		NO	NO	
144	647.0	5.999	3.020	355	51.5		NO	NO	
87	656.0	6.002	3.025	358	52.0		NO	NO	
2	657.0	5.999	3.015	361	52.4		NO	NO	
63	670.0	6.022	3.023	365	53.0		NO	NO	
165	656.0	5.992	2.995	366	53.1		NO	NO	
61	684.0	5.999	3.023	374	54.3		NO	NO	
80	701.0	6.017	3.018	384	55.7		NO	NO	
112	713.0	6.055	3.028	385	55.9		NO	NO	
160	708.0	5.999	3.025	387	56.1		NO	NO	
132	712.0	6.005	3.012	392	56.9		NO	NO	
126	726.0	5.999	3.020	398	57.7		NO	NO	
34	736.0	5.997	3.023	403	58.4		NO	NO	
36	742.0	6.012	3.010	409	59.3		NO	NO	
				MEAN					
				341					
				STD					
				48					

Alumina, 3 mm x 6 mm, 4 pt, MIL-STD-1942 (MR), MTL (Quinn)

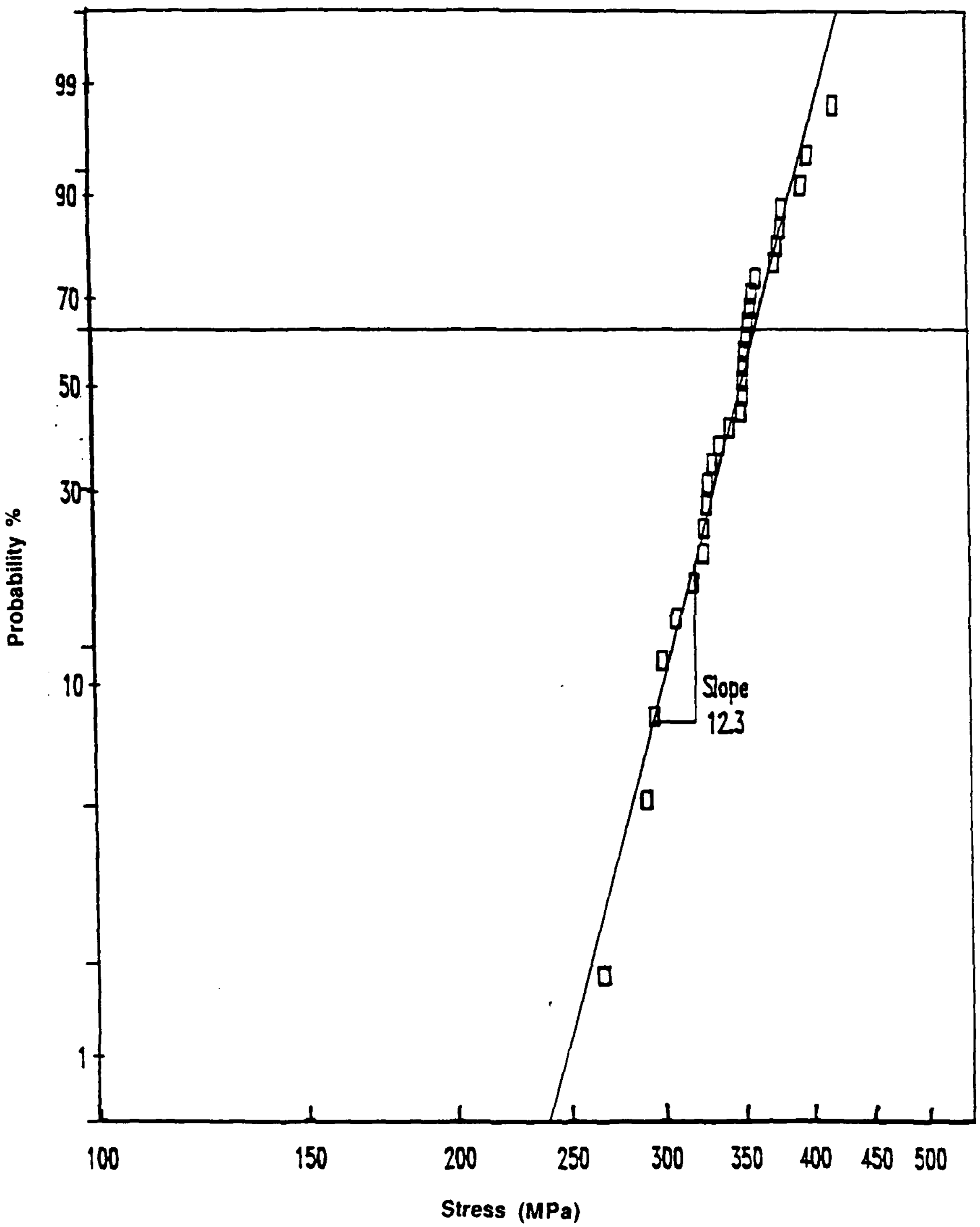


Alumina, 3 mm x 6 mm, 4 pt, MIL-STD-1942 (MR), NPL (Morrell)

MATERIAL	AD-999	VINTAGE	1985, LOT 2
BILLET NO.		1/4 POINT BEND	
C.H SPEED	.5 mm/min	SPECIMEN SIZE	3X6 mm
TEMP	23-24 C	Characteristic Strength of B.B	360 MPA
HUMIDITY	29.5-28.5%	SLOPE	12.28
TESTER		CHART SPEED	N/A
MOMENT ARM	10 mm		

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
94	N/A	6.0	3.0	266	38.6				
169	N/A	6.0	3.0	290	42.1				
65	N/A	6.0	3.0	295	42.8				
93	N/A	6.0	3.0	299	43.4				
143	N/A	6.0	3.0	308	44.7				
19	N/A	6.0	3.0	318	46.1				
27	N/A	6.0	3.0	324	47.0				
102	N/A	6.0	3.0	325	47.1				
139	N/A	6.0	3.0	327	47.4				
71	N/A	6.0	3.0	328	47.6				
48	N/A	6.0	3.0	331	48.0				
129	N/A	6.0	3.0	336	48.7				
114	N/A	6.0	3.0	342	49.6				
138	N/A	6.0	3.0	351	50.9				
55	N/A	6.0	3.0	351	50.9				
16	N/A	6.0	3.0	352	51.1				
146	N/A	6.0	3.0	352	51.1				
17	N/A	6.0	3.0	352	51.1				
24	N/A	6.0	3.0	354	51.3				
134	N/A	6.0	3.0	355	51.5				
120	N/A	6.0	3.0	357	51.8				
136	N/A	6.0	3.0	358	51.9				
41	N/A	6.0	3.0	361	52.4				
148	N/A	6.0	3.0	374	54.2				
60	N/A	6.0	3.0	377	54.7				
43	N/A	6.0	3.0	379	55.0				
9	N/A	6.0	3.0	380	55.1				
153	N/A	6.0	3.0	395	57.3				
7	N/A	6.0	3.0	399	57.9				
154	N/A	6.0	3.0	419	60.8				
				MEAN 345					
				STD 34					

Alumina, 3 mm x 6 mm, 4 pt, MIL-STD-1942 (MR), NPL (Morrell)

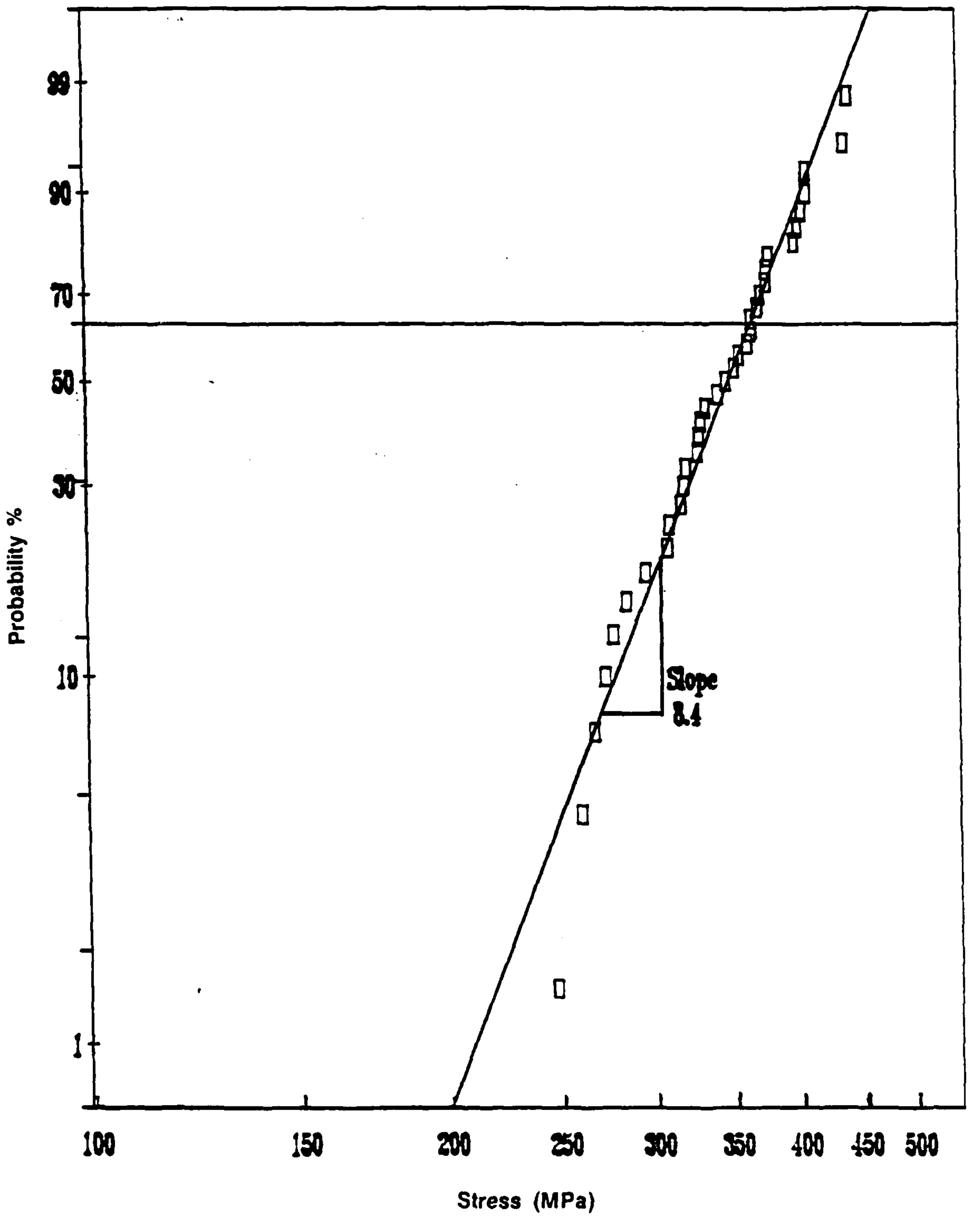


Alumina ,1/4" x 1/8", 4 pt, Current Fixture, IITRI

MATERIAL	AD-999	VINTAGE	
BILLET NO.		IITRI 0.875/1.750 in.	
C.H SPEED		SPECIMEN SIZE	0.125 x 0.250 in.
TEMP		Characteristic Strength	
HUMIDITY		of B.B	363 MPA
TESTER		SLOPE	8.354
MOMENT ARM	11.113 mm	CHART SPEED	

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
12	N/A	6.35	3.18	247	35.8				
34	N/A	6.35	3.18	259	37.6				
7	N/A	6.35	3.18	266	38.6				
6	N/A	6.35	3.18	272	39.4				
28	N/A	6.35	3.18	276	40.1				
18	N/A	6.35	3.18	283	41.1				
32	N/A	6.35	3.18	294	42.7				
35	N/A	6.35	3.18	307	44.5				
16	N/A	6.35	3.18	308	44.7				
26	N/A	6.35	3.18	316	45.8				
10	N/A	6.35	3.18	317	46.0				
31	N/A	6.35	3.18	318	46.2				
13	N/A	6.35	3.18	326	47.3				
20	N/A	6.35	3.18	327	47.4				
2	N/A	6.35	3.18	328	47.6				
27	N/A	6.35	3.18	331	48.0				
29	N/A	6.35	3.18	340	49.3				
19	N/A	6.35	3.18	345	50.1				
15	N/A	6.35	3.18	351	50.9				
25	N/A	6.35	3.18	354	51.4				
33	N/A	6.35	3.18	360	52.3				
4	N/A	6.35	3.18	363	52.6				
22	N/A	6.35	3.18	363	52.6				
8	N/A	6.35	3.18	367	53.3				
24	N/A	6.35	3.18	369	53.6				
30	N/A	6.35	3.18	374	54.3				
21	N/A	6.35	3.18	374	54.3				
3	N/A	6.35	3.18	376	54.5				
5	N/A	6.35	3.18	396	57.4				
14	N/A	6.35	3.18	398	57.8				
23	N/A	6.35	3.18	401	58.2				
9	N/A	6.35	3.18	405	58.7				
1	N/A	6.35	3.18	405	58.7				
11	N/A	6.35	3.18	436	63.2				
17	N/A	6.35	3.18	439	63.7				
				MEAN					
				343					
				STD					
				48.8					

Alumina, 1/4" x 1/8", 4 pt, Current Fixture, IITRI

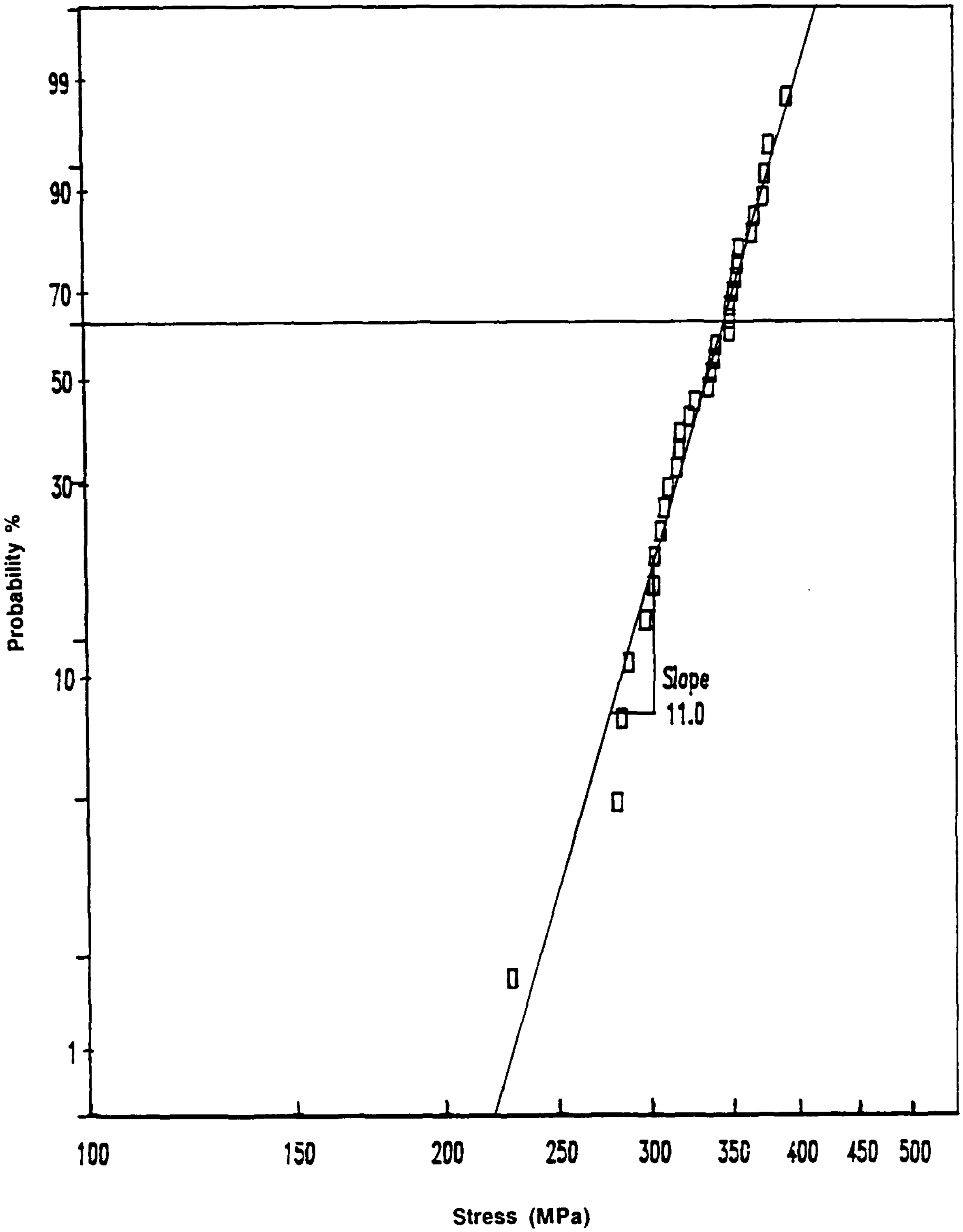


Alumina, 6 mm x 8 mm, 4 pt, MIL-STD-1942 (MR), MTL (Quinn)

MATERIAL	COORS AD-999, A12VINTAGE		
BILLET NO.		4 POINT BEND	
C.H SPEED	1.0	SPECIMEN SIZE	C
TEMP	79°	Characteristic Strength	
HUMIDITY	39%	of B.B	345 MPA
TESTER	S.WESTELMAN	SLOPE	11.02
MOMENT ARM	20 mm	CHART SPEE	100 mm/min

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
12	1074.0	7.898	5.994	227	32.9				
30	1354.0	8.028	6.016	280	40.6				
22	1368.0	8.032	6.016	282	41.0				
2	1386.0	8.034	6.014	286	41.5				
9	1398.0	7.892	5.990	296	43.0				
4	1424.0	7.894	5.996	301	43.7				
15	1458.0	8.022	6.012	302	43.8				
26	1442.0	7.890	5.998	305	44.2				
31	1476.0	8.016	5.998	307	44.5				
11	1498.0	8.022	6.014	310	44.9				
6	1522.0	8.022	6.014	315	45.6				
32	1528.0	8.026	6.010	316	45.9				
23	1536.0	8.030	6.016	317	46.0				
27	1562.0	8.024	6.016	323	46.8				
3	1580.0	8.028	6.016	326	47.3				
20	1618.0	8.016	6.010	335	48.6				
21	1630.0	8.030	6.010	337	48.9				
18	1646.0	8.030	6.020	339	49.2				
25	1644.0	8.026	6.010	340	49.3				
10	1690.0	8.030	6.014	349	50.6				
8	1694.0	8.030	6.018	349	50.7				
24	1652.0	7.900	5.990	350	50.7				
28	1702.0	8.018	6.018	352	51.0				
13	1704.0	8.020	6.004	354	51.3				
16	1720.0	8.030	6.020	355	51.4				
19	1720.0	8.028	6.012	356	51.6				
5	1728.0	7.888	5.999	365	53.0				
14	1776.0	8.022	6.016	367	53.2				
33	1820.0	8.022	6.040	373	54.1				
7	1820.0	8.040	6.022	375	54.3				
29	1832.0	8.032	6.020	378	54.8				
17	1888.0	8.010	6.014	391	56.7				
				MEAN					
				330					
				STD					
				35					

Alumina, 6 mm x 8 mm, 4 pt, MIL-STD-1942 (MR), MTL (Quinn)

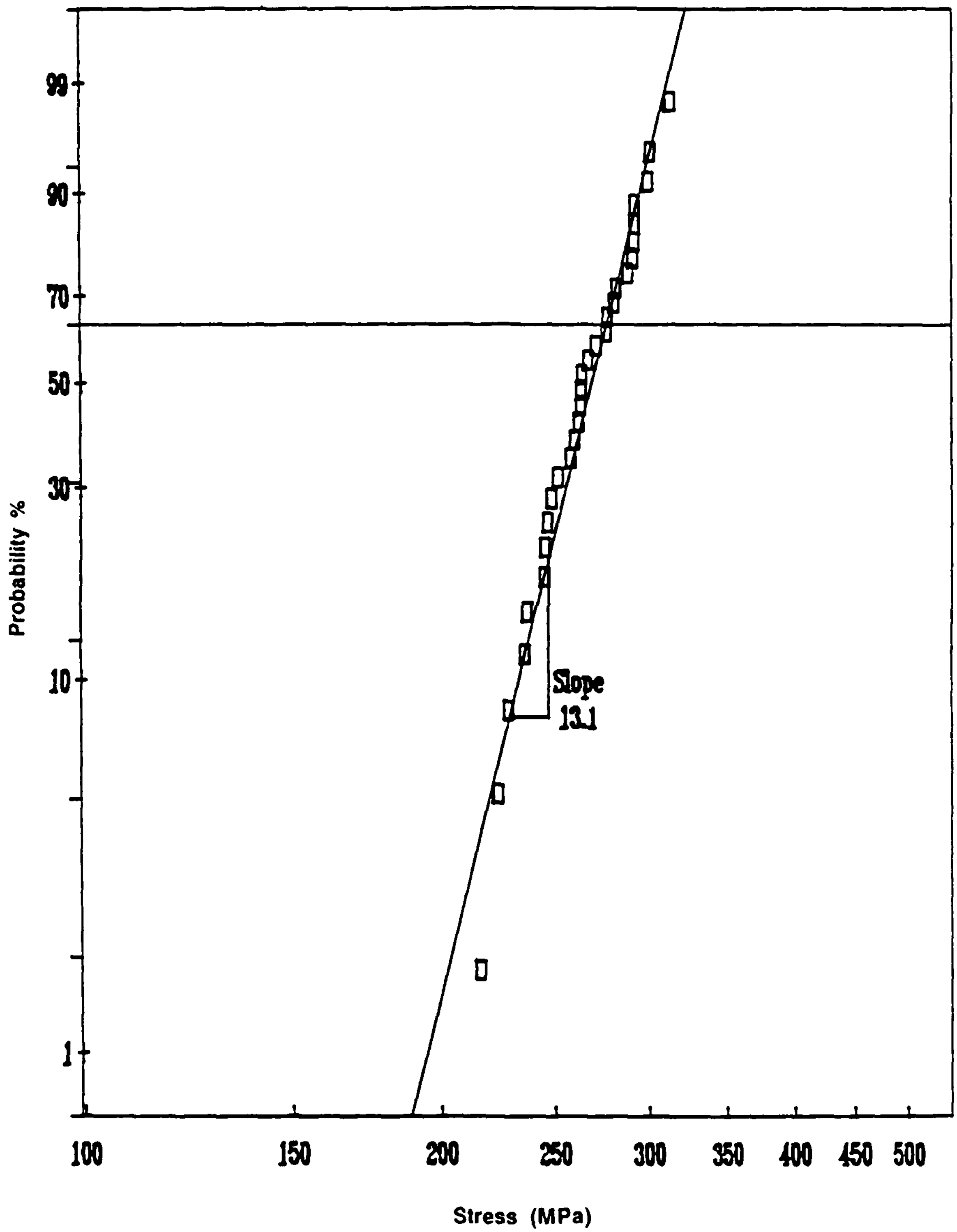


RBSN, 3 mm x 4 mm, 3 pt, Current Fixture, ARE (Godfrey)

MATERIAL	RBSN	VINTAGE
BILLET NO.	2511	3 PT, ARE FIXTURE
C.H SPEED	2.0 mm/min	SPECIMEN SIZE MIL-STD B, 3X4mm
TEMP		Characteristic Strength
HUMIDITY		of B.B 276 MPA
TESTER		SLOPE 13.06
MOMENT ARM	20 mm	CHART SPEED

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
1	N/A	4.0	3.0	216	31.2				
2	N/A	4.0	3.0	224	32.4				
3	N/A	4.0	3.0	228	33.0				
4	N/A	4.0	3.0	236	34.1				
5	N/A	4.0	3.0	237	34.3				
6	N/A	4.0	3.0	245	35.5				
7	N/A	4.0	3.0	245	35.5				
8	N/A	4.0	3.0	246	35.7				
9	N/A	4.0	3.0	248	36.0				
10	N/A	4.0	3.0	251	36.4				
11	N/A	4.0	3.0	258	37.3				
12	N/A	4.0	3.0	260	37.6				
13	N/A	4.0	3.0	262	37.9				
14	N/A	4.0	3.0	263	38.1				
15	N/A	4.0	3.0	263	38.1				
16	N/A	4.0	3.0	264	38.2				
17	N/A	4.0	3.0	267	38.6				
18	N/A	4.0	3.0	271	39.2				
19	N/A	4.0	3.0	276	40.0				
20	N/A	4.0	3.0	277	40.1				
21	N/A	4.0	3.0	280	40.6				
22	N/A	4.0	3.0	282	40.8				
23	N/A	4.0	3.0	288	41.7				
24	N/A	4.0	3.0	291	42.1				
25	N/A	4.0	3.0	292	42.2				
26	N/A	4.0	3.0	292	42.2				
27	N/A	4.0	3.0	292	42.3				
28	N/A	4.0	3.0	299	43.3				
29	N/A	4.0	3.0	301	43.5				
30	N/A	4.0	3.0	312	45.3				
				MEAN					
				265					
				STD					
				24					

RBSN, 3 mm x 4 mm, 3 pt, Current Fixture, ARE (Godfrey)



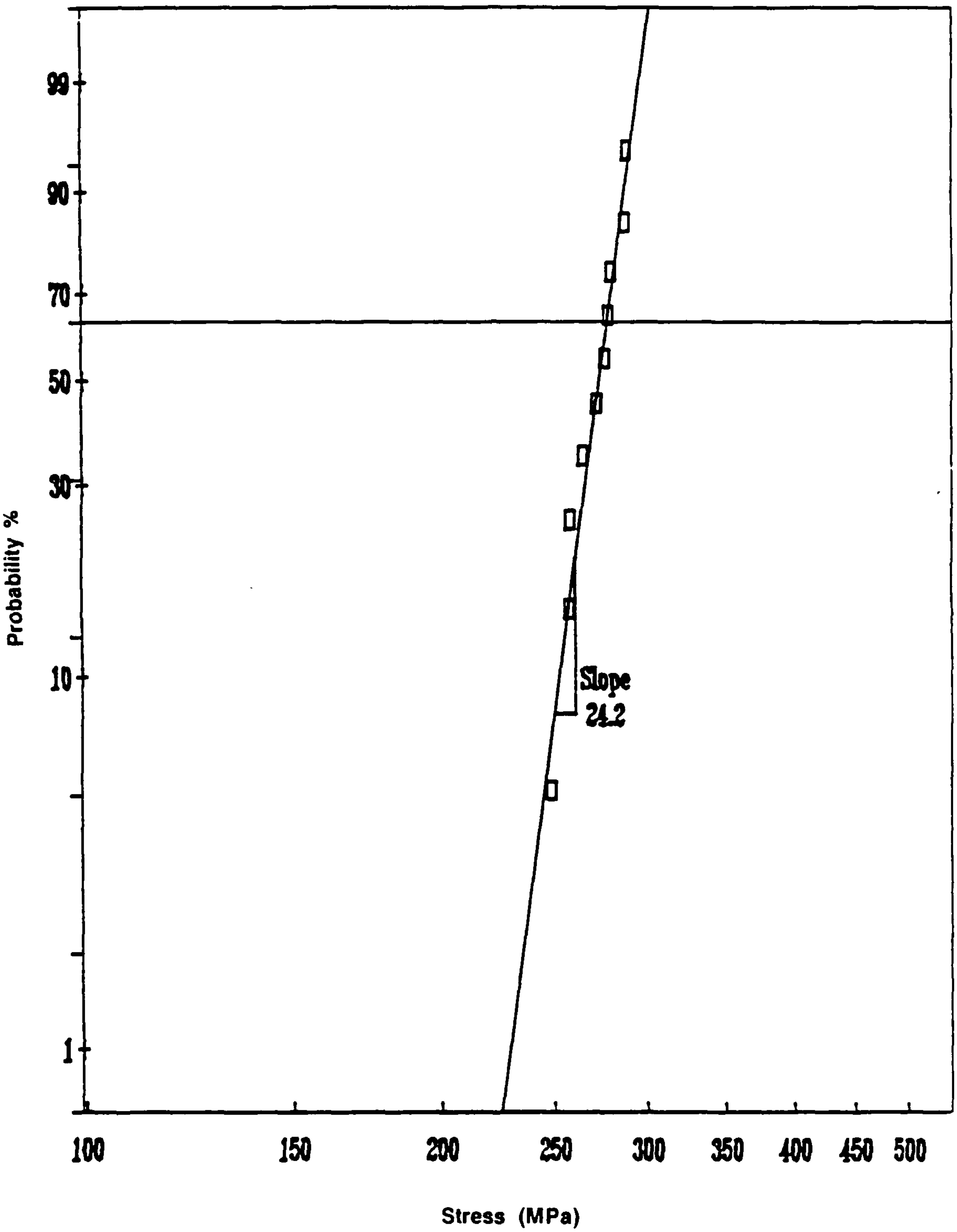
RBSN, 3 mm x 4 mm, 3 pt, MIL-STD-1942 (MR), ARE (Godfrey)

MATERIAL	RBSN	VINTAGE	
BILLET NO.	2510	3 PT, MIL-STD B	
C.H SPEED	2.0 mm/min*	SPECIMEN SIZE	MIL-STD B, 3X4mm
TEMP		Characteristic Strength	
HUMIDITY		of B.B	276 MPA
TESTER		SLOPE	24.19
MOMENT ARM	20 mm	CHART SPEED	

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
1	N/A	4.0	3.0	248	35.9				
2	N/A	4.0	3.0	257	37.3				
3	N/A	4.0	3.0	258	37.3				
4	N/A	4.0	3.0	264	38.3				
5	N/A	4.0	3.0	271	39.3				
6	N/A	4.0	3.0	276	39.9				
7	N/A	4.0	3.0	277	40.2				
8	N/A	4.0	3.0	279	40.4				
9	N/A	4.0	3.0	287	41.6				
10	N/A	4.0	3.0	288	41.6				
				MEAN 271					
				STD 13					

*A crosshead speed of 0.5 mm/min should have been used.

RBSN, 3 mm x 4 mm, 3 pt, Current Fixture, ARE (Godfrey)

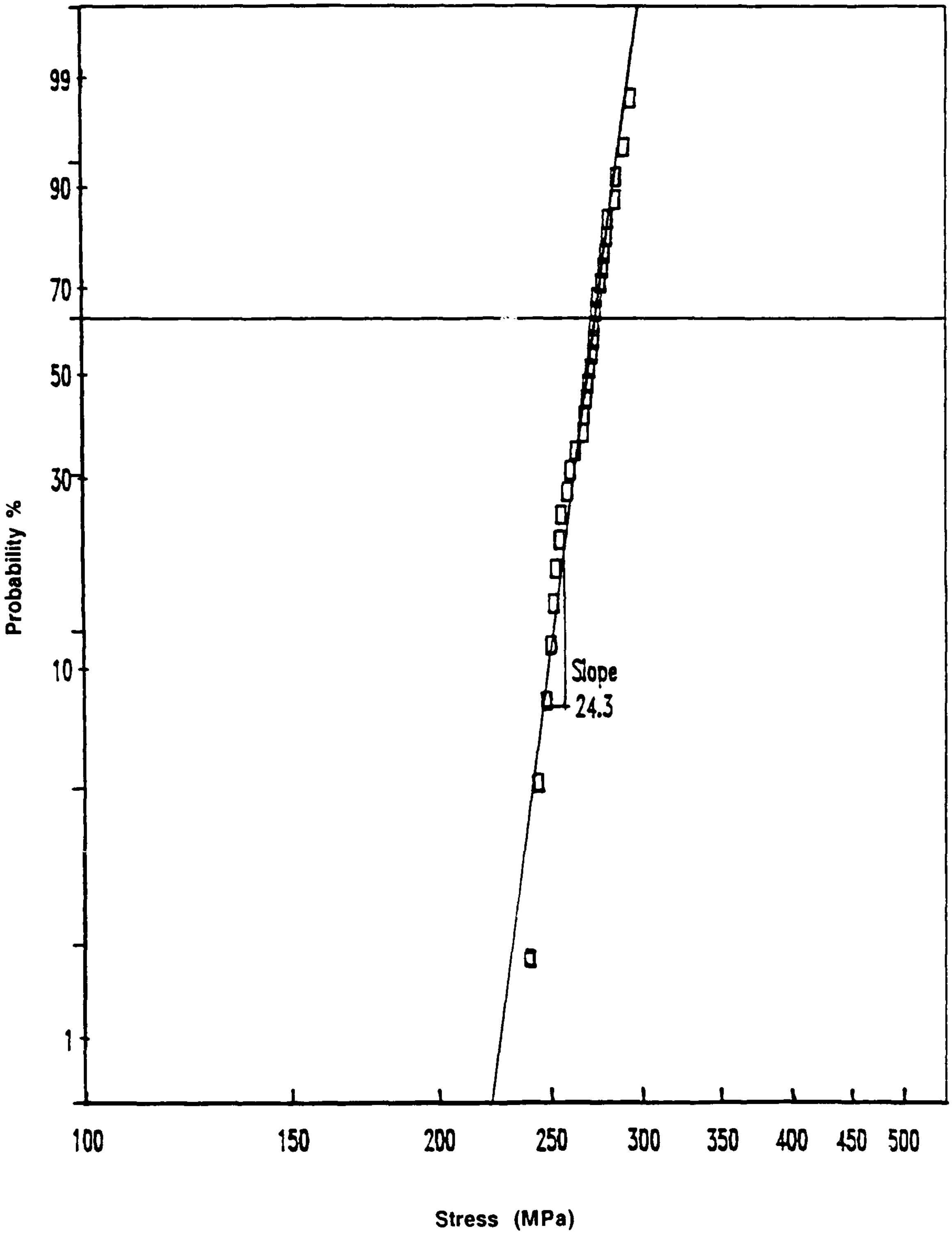


RBSN, 3 mm x 4 mm, 3 pt, MIL-STD-1942 (MR), MTL (Quinn)

MATERIAL	RBSN (AS-FIRED)	VINTAGE	
BILLET NO.	2510 & 2511	3 POINT BEND	
C.H SPEED	.5mm/min	SPECIMEN SIZE	MIL-STD B
TEMP	74 F	Characteristic Strength	
HUMIDITY	33%	of B.B	273 MPA
TESTER	G. QUINN, MTL	SLOPE	24.29
MOMENT ARM	20 mm	CHART SPEED	100 mm/min

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
148	147.8	4.029	3.030	240	34.8		NO	NO	2510
200	147.6	4.023	3.005	244	35.4		NO	NO	2511
124	152.4	4.015	3.029	248	36.0		NO	NO	2510
160	151.6	4.020	3.007	250	36.3		NO	NO	2510
196	154.2	4.029	3.023	251	36.4		NO	NO	2510
152	153.0	4.016	3.011	252	36.6		NO	NO	2511
176	157.2	4.027	3.036	254	36.9		NO	NO	2511
17	157.8	4.016	3.041	255	37.0		NO	NO	2511
171	157.2	4.020	3.014	258	37.5		NO	NO	2510
232	158.6	4.032	3.014	260	37.7		NO	NO	2510
3	161.0	4.034	3.020	263	38.1		NO	NO	2511
208	163.6	4.033	3.022	267	38.7		NO	NO	2510
15	163.8	4.044	3.017	267	38.7		NO	NO	2511
220	164.0	4.019	3.023	268	38.9		NO	NO	2510
207	163.0	4.020	3.009	269	39.0		NO	NO	2510
147	166.0	4.015	3.032	270	39.1		NO	NO	2510
219	165.2	4.025	3.013	271	39.3		NO	NO	2510
136	164.6	4.001	3.014	272	39.4		NO	NO	2510
159	164.0	4.000	3.007	272	39.5		NO	NO	2510
231	165.8	4.036	3.005	273	39.6		NO	NO	2510
164	165.6	4.025	3.006	273	39.6		NO	NO	2511
186	168.6	4.022	3.020	276	40.0		NO	NO	2510
39	171.8	4.015	3.044	277	40.2		NO	NO	2511
135	170.5	4.036	3.020	278	40.3		NO	NO	2510
123	169.6	4.000	3.019	279	40.5		NO	NO	2510
188	171.2	4.016	3.025	280	40.5		NO	NO	2511
195	173.8	4.030	3.019	284	41.2		NO	NO	2510
172	173.4	4.017	3.020	284	41.2		NO	NO	2510
183	175.2	4.020	3.012	288	41.8		NO	NO	2510
51	179.0	4.018	3.028	292	42.3		NO	NO	2511
				MEAN 267					
				STD 13					

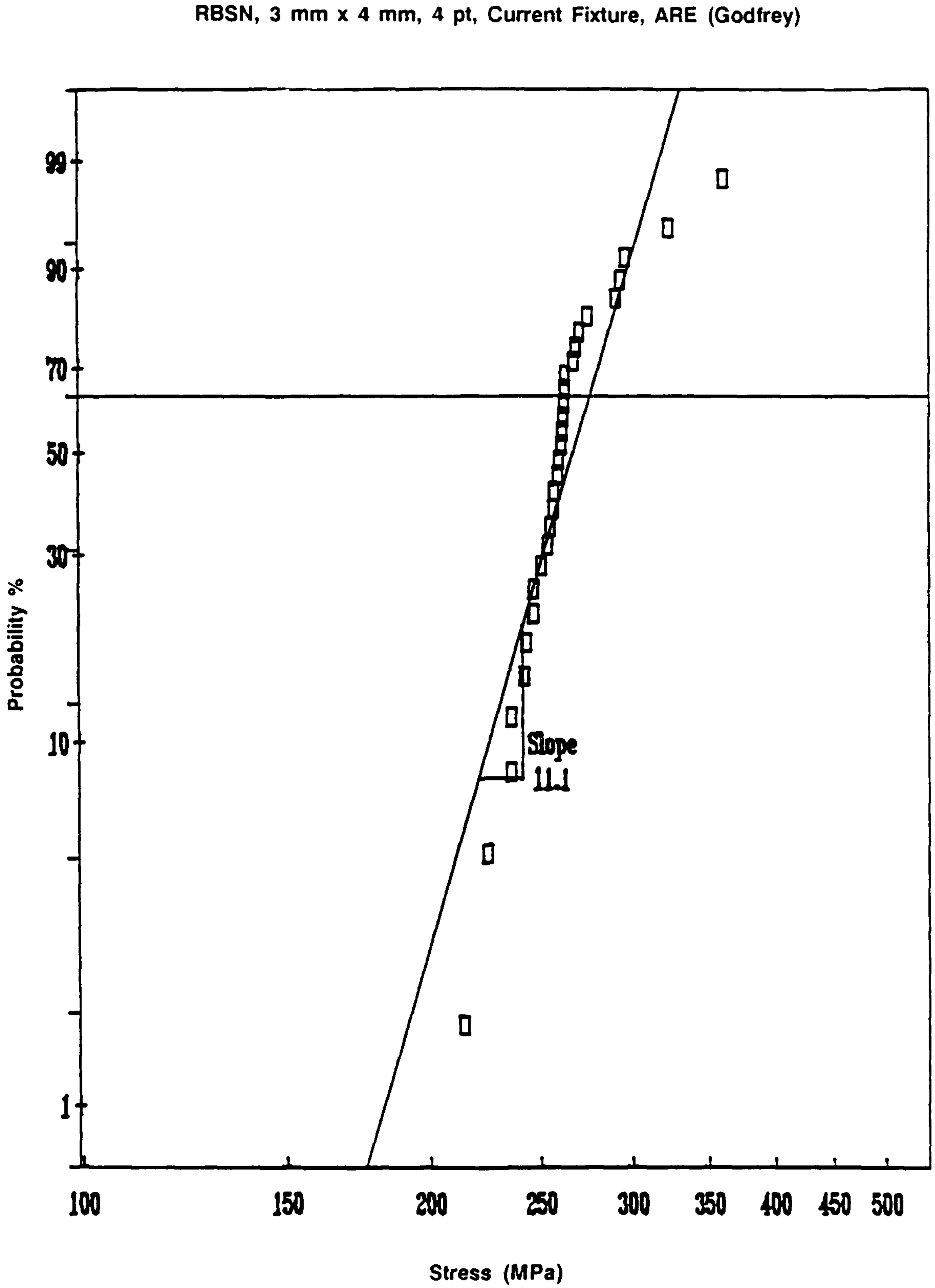
RBSN, 3 mm x 4 mm, 3 pt, MIL-STD-1942 (MR), MTL (Quinn)



RBSN, 3 mm x 4 mm, 4 pt, Current Fixture, ARE (Godfrey)

MATERIAL	RBSN	VINTAGE	
BILLET NO.	2510	4 PT, ARE FIXTURE	
C.H SPEED	2.0 mm/min	SPECIMEN SIZE	MIL-STD B, 3X4 mm
TEMP		Characteristic Strength	
HUMIDITY		of B.B	275 MPA
TESTER		SLOPE	11.11
MOMENT ARM	10.475 mm	CHART SPEED	

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
1	N/A	4.0	3.0	214	31.0				
2	N/A	4.0	3.0	225	32.5				
3	N/A	4.0	3.0	236	34.1				
4	N/A	4.0	3.0	236	34.1				
5	N/A	4.0	3.0	242	35.0				
6	N/A	4.0	3.0	243	35.2				
7	N/A	4.0	3.0	247	35.7				
8	N/A	4.0	3.0	247	35.7				
9	N/A	4.0	3.0	250	36.3				
10	N/A	4.0	3.0	254	36.7				
11	N/A	4.0	3.0	255	36.9				
12	N/A	4.0	3.0	257	37.2				
13	N/A	4.0	3.0	257	37.2				
14	N/A	4.0	3.0	259	37.5				
15	N/A	4.0	3.0	259	37.5				
16	N/A	4.0	3.0	260	37.7				
17	N/A	4.0	3.0	261	37.8				
18	N/A	4.0	3.0	261	37.8				
19	N/A	4.0	3.0	262	37.9				
20	N/A	4.0	3.0	262	37.9				
21	N/A	4.0	3.0	262	38.0				
22	N/A	4.0	3.0	267	38.6				
23	N/A	4.0	3.0	268	38.8				
24	N/A	4.0	3.0	270	39.1				
25	N/A	4.0	3.0	274	39.7				
26	N/A	4.0	3.0	290	42.0				
27	N/A	4.0	3.0	292	42.4				
28	N/A	4.0	3.0	295	42.8				
29	N/A	4.0	3.0	322	46.7				
30	N/A	4.0	3.0	360	52.1				
				MEAN 263					
				STD 28					



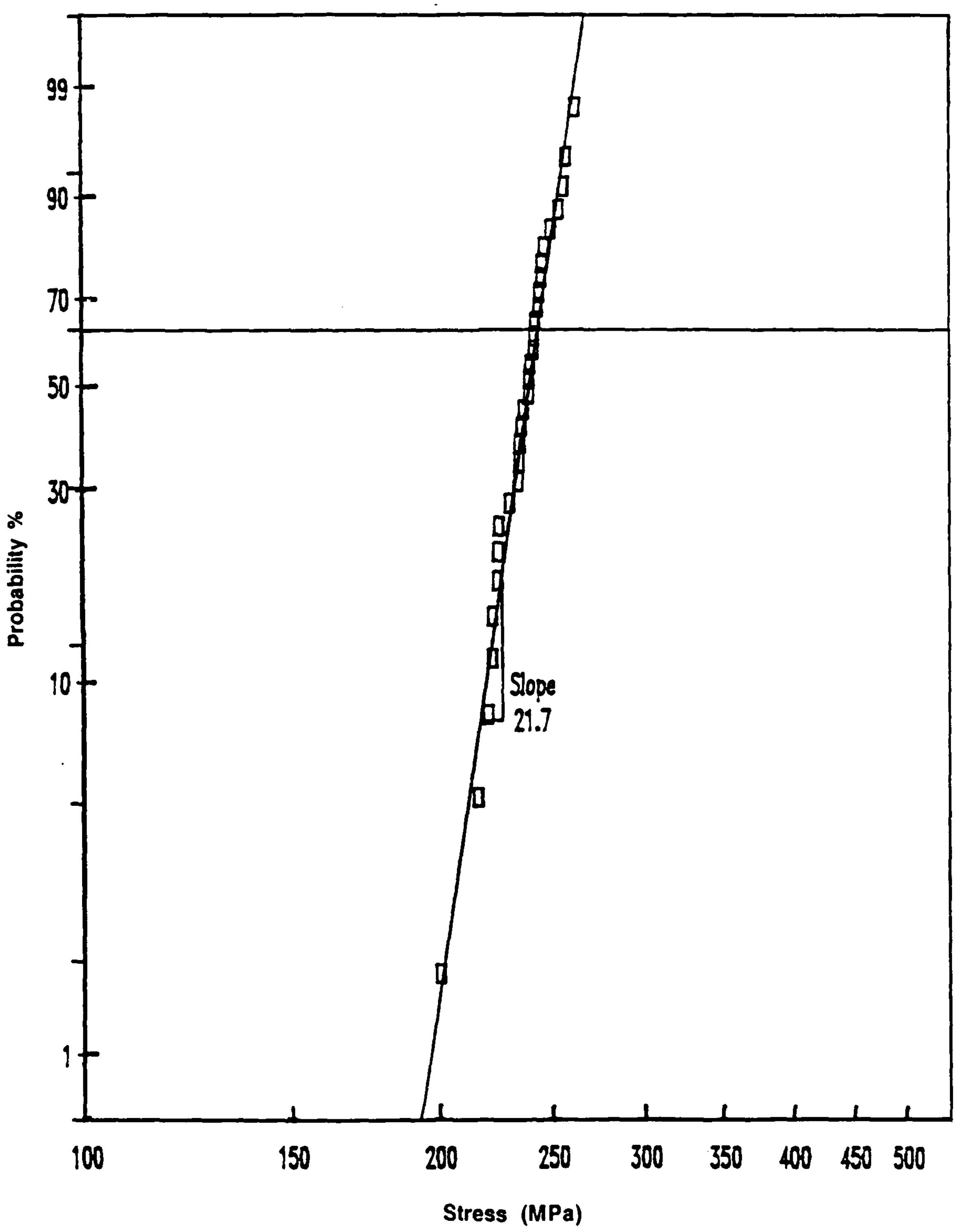
RBSN, 3 mm x 4 mm, 4 pt, Current Fixture, ARE (Godfrey)
Probability %
99
90
70
50
30
10
1
Slope
11.1
100
150
200
250
300
350
400
450
500
Stress (MPa)

RBSN, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), MTL (Quinn)

MATERIAL	RBSN	VINTAGE	
BILLET NO.		4 POINT BEND	
C.H SPEED	0.5	SPECIMEN SIZE	B
TEMP	79	Characteristic Strength	
HUMIDITY	23	of B.B	243 MPA
TESTER	S.WESTELMAN	SLOPE	21.72
MOMENT ARM	10 mm	CHART SPEED	100

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
16	252.0	4.044	3.053	201	29.1		NO	NO	
63	266.5	4.034	3.028	216	31.4		NO	NO	
87	270.0	4.028	3.020	220	32.0		NO	NO	
99	274.0	4.036	3.028	222	32.2		NO	NO	
15	276.0	4.036	3.038	222	32.2		NO	NO	
52	279.0	4.034	3.038	225	32.6		NO	NO	
28	279.0	4.034	3.038	225	32.6		NO	NO	
64	278.5	4.031	3.033	225	32.7		NO	NO	
27	291.0	4.062	3.056	230	33.4		NO	NO	
111	284.0	4.044	3.000	234	34.0		NO	NO	
39	291.0	4.036	3.038	234	34.0		NO	NO	
76	289.5	4.032	3.030	235	34.0		NO	NO	
28	291.0	4.044	3.028	235	34.1		NO	NO	
60	293.0	4.026	3.038	237	34.3		NO	NO	
165	295.5	4.026	3.035	239	34.7		NO	NO	
16	298.5	4.044	3.043	239	34.7		NO	NO	
153	298.5	4.036	3.043	240	34.8		NO	NO	
88	298.0	4.054	3.023	241	35.0		NO	NO	
177	300.5	4.041	3.040	241	35.0		NO	NO	
40	296.5	4.023	3.023	242	35.1		NO	NO	
52	302.5	4.044	3.037	243	35.3		NO	NO	
75	301.0	4.036	3.030	244	35.3		NO	NO	
3	309.5	4.059	3.056	245	35.5		NO	NO	
189	304.0	4.044	3.033	245	35.6		NO	NO	
100	304.5	4.043	3.030	246	35.7		NO	NO	
51	310.0	4.036	3.038	250	36.2		NO	NO	
4	317.0	4.046	3.046	253	36.7		NO	NO	
4	317.0	4.036	3.035	256	37.1		NO	NO	
112	318.0	4.031	3.035	257	37.3		NO	NO	
201	322.5	4.034	3.030	261	37.9		NO	NO	
				MEAN 237					
				STD 13					

RBSN, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), MTL (Quinn)



RBSN, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), IITRI

MATERIAL RBSN
BILLET NO.
C.H SPEED
TEMP
HUMIDITY
TESTER
MOMENT ARM 10 mm

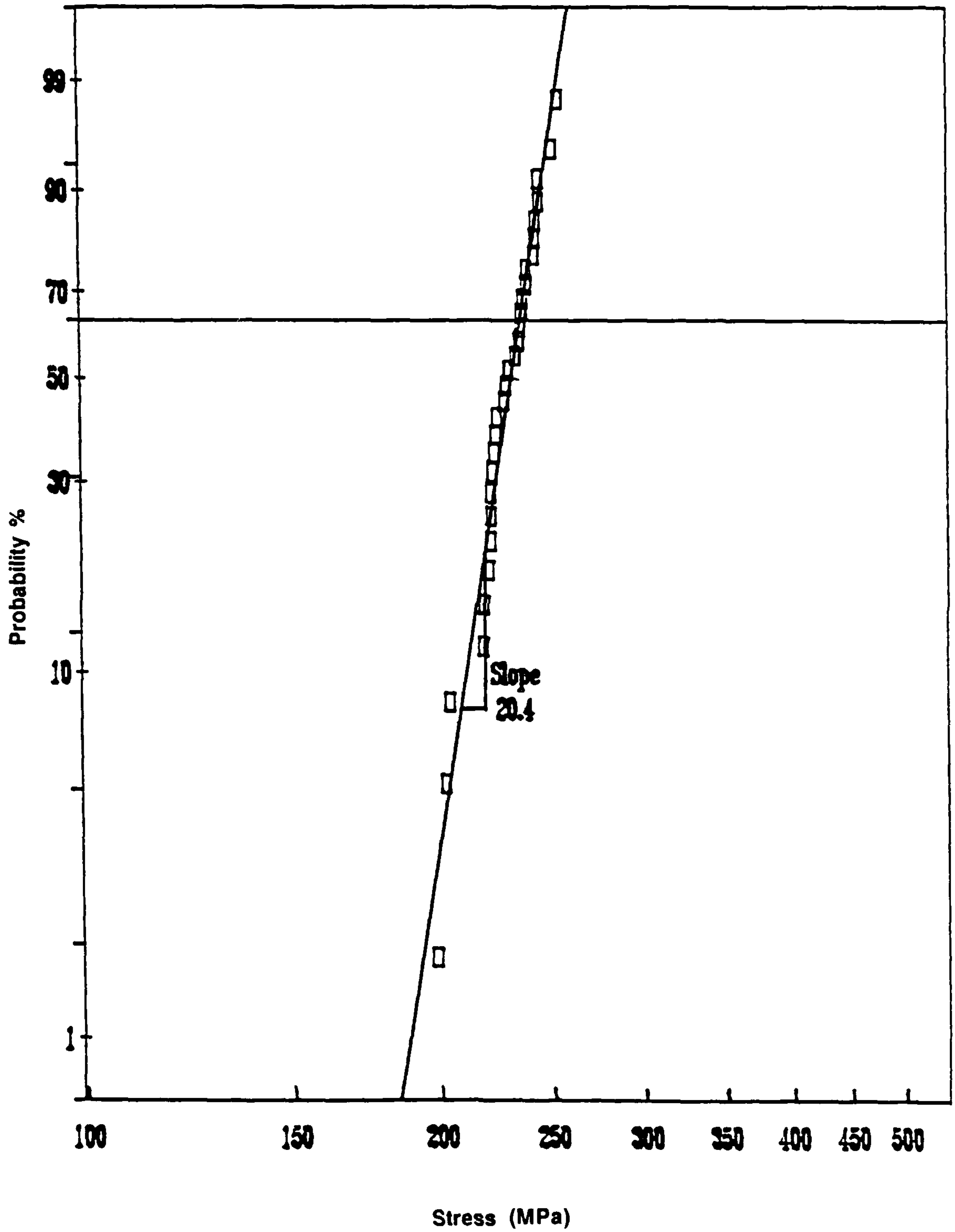
VINTAGE
MIL-STD B
SPECIMEN SIZE MIL-STD B, 3x4 mm
Characteristic Strength
of B.B 236 MPA
SLOPE 20.43
CHART SPEED

===

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
19	N/A	4.0	3.0	199	28.8				
22	N/A	4.0	3.0	202	29.3				
30	N/A	4.0	3.0	204	29.6				
3	N/A	4.0	3.0	218	31.7				
8	N/A	4.0	3.0	219	31.7				
28	N/A	4.0	3.0	221	32.0				
9	N/A	4.0	3.0	222	32.2				
20	N/A	4.0	3.0	222	32.2				
10	N/A	4.0	3.0	222	32.2				
26	N/A	4.0	3.0	222	32.3				
13	N/A	4.0	3.0	223	32.4				
4	N/A	4.0	3.0	224	32.5				
14	N/A	4.0	3.0	225	32.6				
27	N/A	4.0	3.0	228	33.1				
16	N/A	4.0	3.0	229	33.2				
6	N/A	4.0	3.0	230	33.4				
18	N/A	4.0	3.0	233	33.8				
1	N/A	4.0	3.0	235	34.1				
2	N/A	4.0	3.0	236	34.2				
7	N/A	4.0	3.0	236	34.2				
5	N/A	4.0	3.0	237	34.4				
17	N/A	4.0	3.0	238	34.6				
11	N/A	4.0	3.0	239	34.6				
12	N/A	4.0	3.0	242	35.1				
21	N/A	4.0	3.0	242	35.2				
29	N/A	4.0	3.0	243	35.2				
25	N/A	4.0	3.0	244	35.5				
24	N/A	4.0	3.0	245	35.5				
15	N/A	4.0	3.0	251	36.4				
23	N/A	4.0	3.0	254	36.9				

MEAN
230
STD
13.3

RBSN, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), IITRI

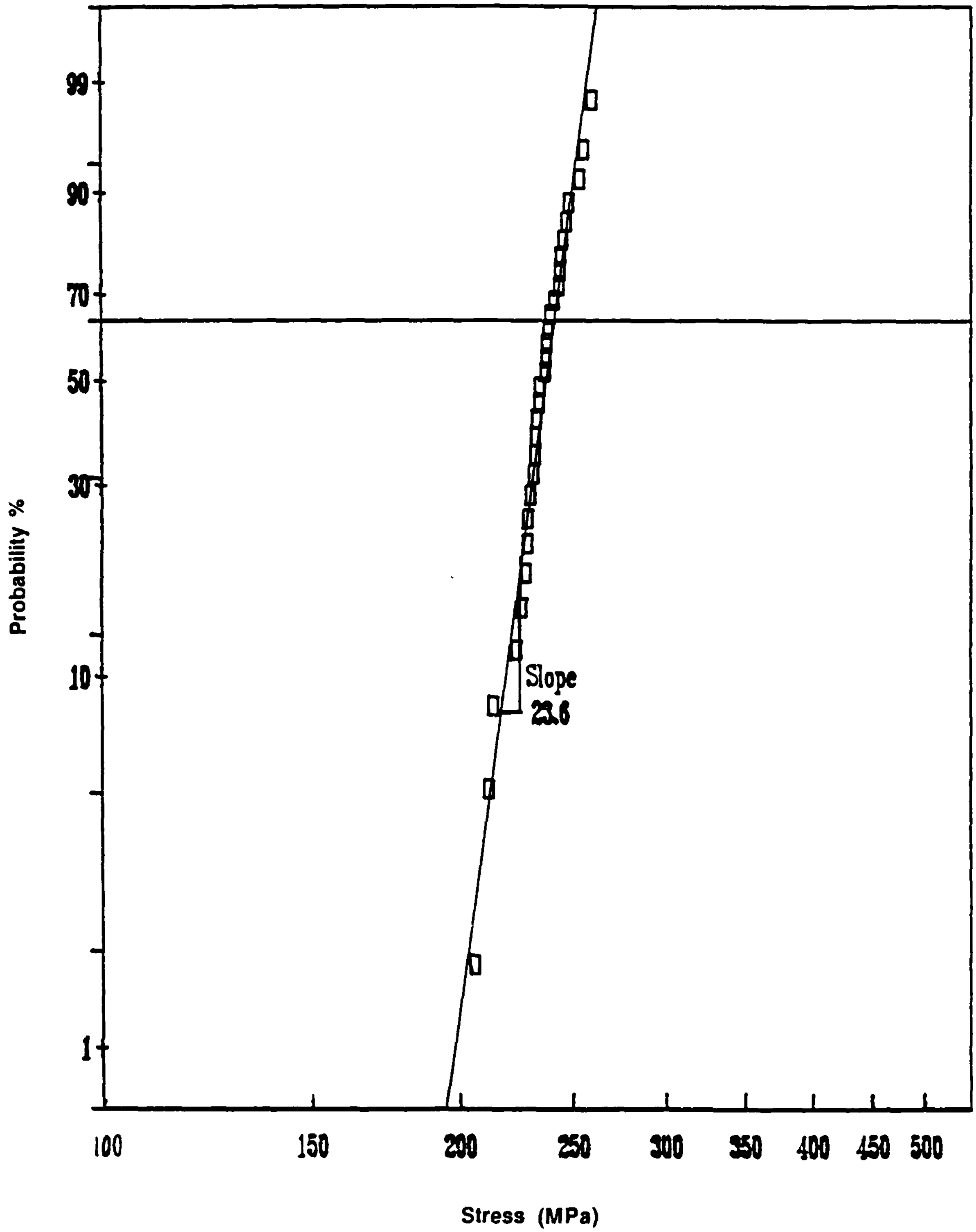


RBSN, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), ORF (Sullivan)

MATERIAL	RBSN	VINTAGE	
BILLET NO.	2510 & 2511	1/4 POINT BEND	
C.H SPEED	.5 mm/min	SPECIMEN SIZE	MIL-STD B
TEMP	23 C	Characteristic Strength	
HUMIDITY	58%	of B.B	240 MPA
TESTER	LAUZON/SULLIVAN	SLOPE	23.64
MOMENT ARM	10 mm	CHART SPEED	

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
122	258.1	4.045	3.052	206	29.8				#2510
166	263.4	4.026	3.047	211	30.7				#2510
86	263.0	4.034	3.029	213	30.9				#2510
14	280.8	4.043	3.055	223	32.4				#2511
16	280.8	4.035	3.042	226	32.7				#2510
26	286.1	4.036	3.059	227	33.0				#2511
38	279.0	4.018	3.024	228	33.0				#2511
175	283.5	4.046	3.035	228	33.1				#2511
151	293.7	4.043	3.084	229	33.2				#2511
136	286.6	4.030	3.040	231	33.5				#2510
50	290.1	4.040	3.052	231	33.5				#2510
163	285.3	4.038	3.024	232	33.6				#2511
50	287.0	4.030	3.034	232	33.7				#2511
218	290.1	4.047	3.035	233	33.9				#2510
206	292.8	4.042	3.050	234	33.9				#2510
196	300.4	4.046	3.070	236	34.3				#2510
38	299.0	4.031	3.066	237	34.3				#2510
158	287.5	4.013	3.010	237	34.4				#2510
230	296.8	4.035	3.048	238	34.5				#2510
2	300.4	4.061	3.050	239	34.6				#2511
26	300.8	4.055	3.043	240	34.9				#2510
2	307.1	4.050	3.063	242	35.2				#2510
62	304.8	4.046	3.051	243	35.2				#2510
199	301.7	4.030	3.037	244	35.3				#2511
110	304.8	4.040	3.043	244	35.5				#2510
98	311.1	4.046	3.060	246	35.7				#2510
170	307.5	4.037	3.039	247	35.9				#2510
182	314.2	4.026	3.043	253	36.7				#2510
74	316.0	4.027	3.039	255	37.0				#2510
189	320.0	4.032	3.034	259	37.5				#2511
				MEAN					
				234.					
				STD					
				11.9					

RBSN, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), ORF (Sullivan)



RBSN, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), ARE (Godfrey)

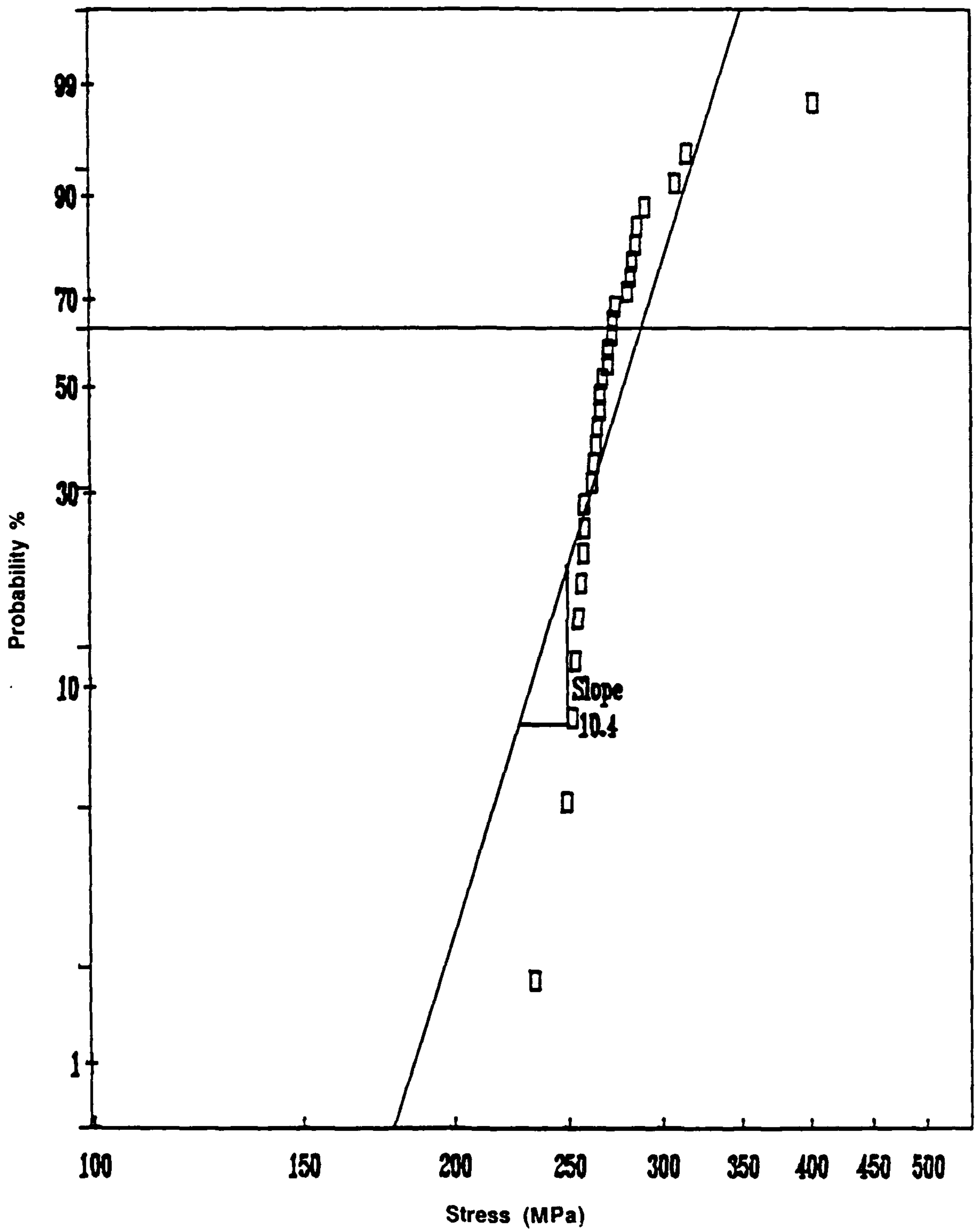
MATERIAL	RBSN	VINTAGE	
BILLET NO.	2511	4 PT, MIL-STD B	
C.H SPEED	2.0 mm/min*	SPECIMEN SIZE	MIL-STD B, 3X4mm
TEMP		Characteristic Strength	
HUMIDITY		of B.B	288 MPA
TESTER		SLOPE	10.39
MOMENT ARM	10 mm	CHART SPEED	

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
1	N/A	4.0	3.0	234	33.9				
2	N/A	4.0	3.0	249	36.0				
3	N/A	4.0	3.0	252	36.5				
4	N/A	4.0	3.0	253	36.7				
5	N/A	4.0	3.0	255	36.9				
6	N/A	4.0	3.0	256	37.1				
7	N/A	4.0	3.0	257	37.2				
8	N/A	4.0	3.0	258	37.3				
9	N/A	4.0	3.0	258	37.3				
10	N/A	4.0	3.0	262	37.9				
11	N/A	4.0	3.0	262	38.0				
12	N/A	4.0	3.0	264	38.2				
13	N/A	4.0	3.0	264	38.3				
14	N/A	4.0	3.0	266	38.5				
15	N/A	4.0	3.0	266	38.5				
16	N/A	4.0	3.0	267	38.7				
17	N/A	4.0	3.0	270	39.1				
18	N/A	4.0	3.0	270	39.1				
19	N/A	4.0	3.0	272	39.3				
20	N/A	4.0	3.0	272	39.4				
21	N/A	4.0	3.0	274	39.6				
22	N/A	4.0	3.0	280	40.6				
23	N/A	4.0	3.0	282	40.9				
24	N/A	4.0	3.0	283	41.0				
25	N/A	4.0	3.0	285	41.3				
26	N/A	4.0	3.0	286	41.4				
27	N/A	4.0	3.0	290	42.0				
28	N/A	4.0	3.0	307	44.5				
29	N/A	4.0	3.0	314	45.5				
30	N/A	4.0	3.0	402	58.2				
				MEAN 274					
				STD 29					

*A crosshead rate of 0.5 mm/min should have been used.

Note: The highest strength datum has an unusually strong effect upon the Weibull graph. If it is deleted, m = 18.7, and characteristic strength of the bend bar is 277 MPa. The data still has a curvature to it, however.

RBSN, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), ARE (Godfrey)

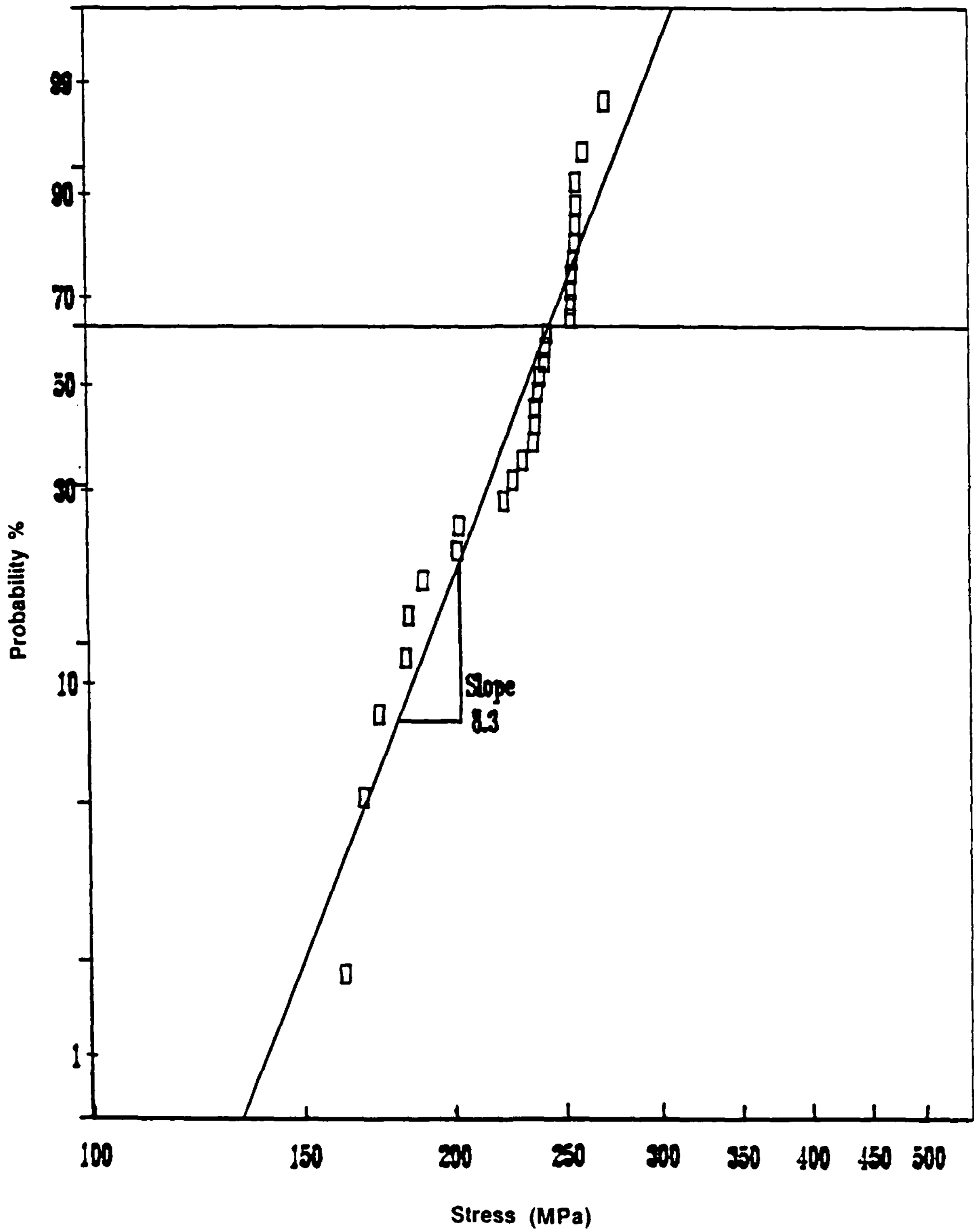


RBSN, 3 mm x 4 mm, 4 pt, Modified Fixture, IITRI

MATERIAL	RBSN	VINTAGE	
BILLET NO.		IITRI 20/40 mm	
C.H SPEED		SPECIMEN SIZE	MIL-STD B, 3x4 mm
TEMP		Characteristic Strength	
HUMIDITY		of B.B	243 MPA
TESTER		SLOPE	8.317
MOMENT ARM	10 mm	CHART SPEED	

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
1	N/A	4.0	3.0	162	23.5				
21	N/A	4.0	3.0	168	24.4				
5	N/A	4.0	3.0	174	25.2				
2	N/A	4.0	3.0	183	26.5				
10	N/A	4.0	3.0	184	26.7				
30	N/A	4.0	3.0	189	27.5				
19	N/A	4.0	3.0	202	29.3				
14	N/A	4.0	3.0	203	29.5				
25	N/A	4.0	3.0	222	32.2				
26	N/A	4.0	3.0	226	32.8				
13	N/A	4.0	3.0	230	33.4				
17	N/A	4.0	3.0	235	34.1				
9	N/A	4.0	3.0	236	34.2				
3	N/A	4.0	3.0	236	34.2				
6	N/A	4.0	3.0	237	34.4				
22	N/A	4.0	3.0	238	34.6				
27	N/A	4.0	3.0	241	34.9				
28	N/A	4.0	3.0	241	34.9				
20	N/A	4.0	3.0	242	35.1				
15	N/A	4.0	3.0	253	36.7				
4	N/A	4.0	3.0	253	36.8				
7	N/A	4.0	3.0	253	36.8				
24	N/A	4.0	3.0	254	36.8				
18	N/A	4.0	3.0	254	36.9				
12	N/A	4.0	3.0	255	37.1				
11	N/A	4.0	3.0	256	37.1				
29	N/A	4.0	3.0	256	37.1				
16	N/A	4.0	3.0	256	37.1				
23	N/A	4.0	3.0	259	37.6				
8	N/A	4.0	3.0	271	39.3				
				MEAN					
				229.					
				STD					
				30.3					

RBSN, 3 mm x 4 mm, 4 pt, Modified Fixture, IITRI



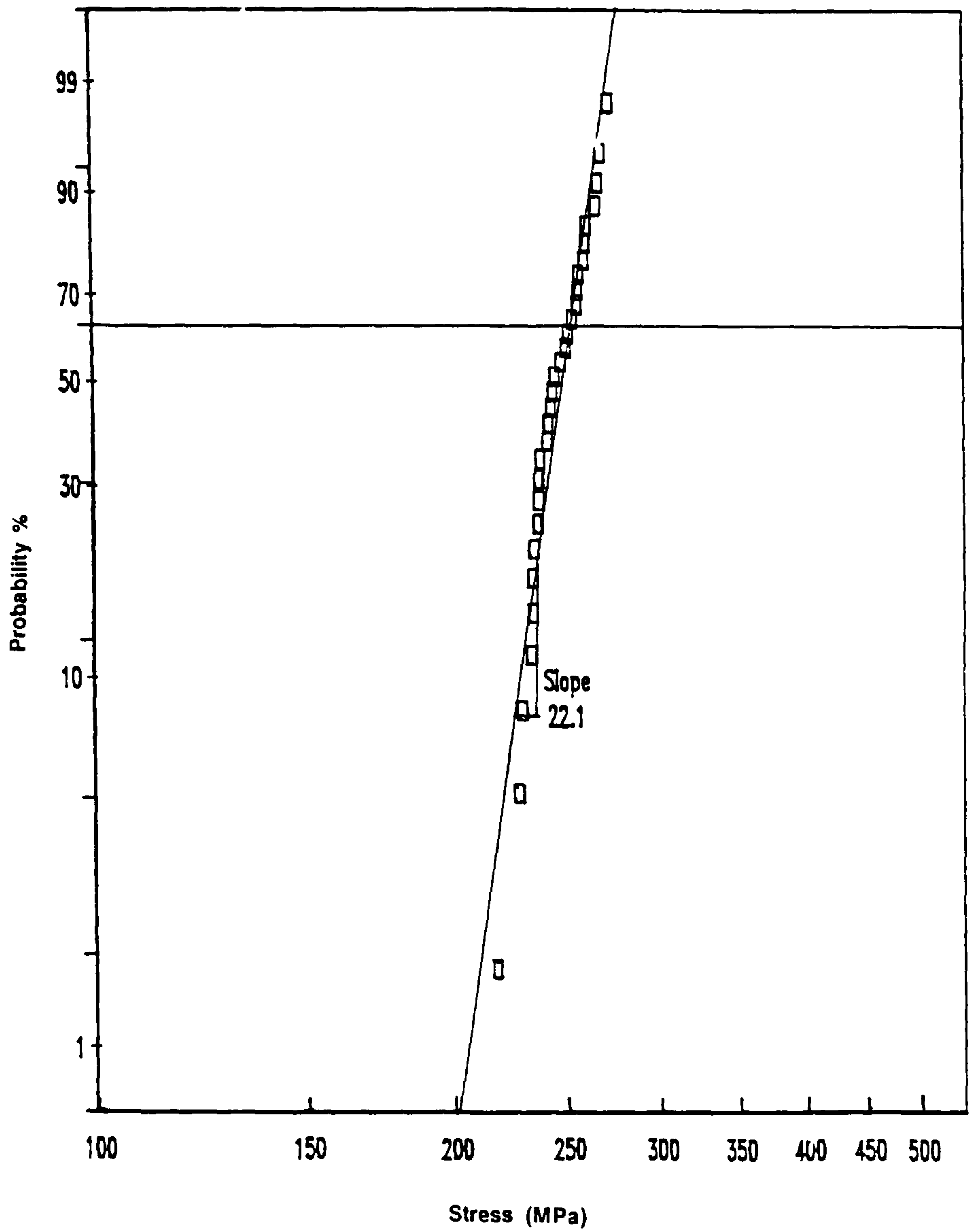
RBSN, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), NPL (Morrell)

MATERIAL RBSN
BILLET NO.
C.H SPEED .5mm/min
TEMP 27 C
HUMIDITY 39.5%
TESTER
MOMENT ARM 10 mm

VINTAGE
1/4 POINT BEND
SPECIMEN SIZE MIL-STD B (3X4mm)
Characteristic Strength
of B.B 252 MPA
SLOPE 22.14
CHART SPEED N/A

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
41	N/A	4.0	3.0	217	31.5				2510
101	N/A	4.0	3.0	227	33.0				2510
113	N/A	4.0	3.0	229	33.2				2510
209	N/A	4.0	3.0	233	33.9				2510
5	N/A	4.0	3.0	234	33.9				2510
154	N/A	4.0	3.0	234	33.9				2511
17	N/A	4.0	3.0	235	34.0				2510
197	N/A	4.0	3.0	237	34.3				2510
125	N/A	4.0	3.0	237	34.4				2510
185	N/A	4.0	3.0	237	34.4				2510
41	N/A	4.0	3.0	237	34.4				2511
161	N/A	4.0	3.0	241	35.0				2510
173	N/A	4.0	3.0	241	35.0				2510
65	N/A	4.0	3.0	243	35.2				2510
53	N/A	4.0	3.0	243	35.3				2510
169	N/A	4.0	3.0	244	35.4				2510
77	N/A	4.0	3.0	247	35.9				2510
89	N/A	4.0	3.0	250	36.2				2510
166	N/A	4.0	3.0	251	36.4				2511
202	N/A	4.0	3.0	253	36.7				2511
221	N/A	4.0	3.0	255	37.0				2510
29	N/A	4.0	3.0	256	37.1				2511
137	N/A	4.0	3.0	256	37.2				2510
178	N/A	4.0	3.0	259	37.6				2511
233	N/A	4.0	3.0	260	37.7				2510
29	N/A	4.0	3.0	260	37.7				2510
190	N/A	4.0	3.0	265	38.5				2511
17	N/A	4.0	3.0	266	38.6				2511
53	N/A	4.0	3.0	268	38.8				2511
5	N/A	4.0	3.0	272	39.4				2511
				MEAN					
				246					
				STD					
				13					

RBSN, 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), NPL (Morrell)

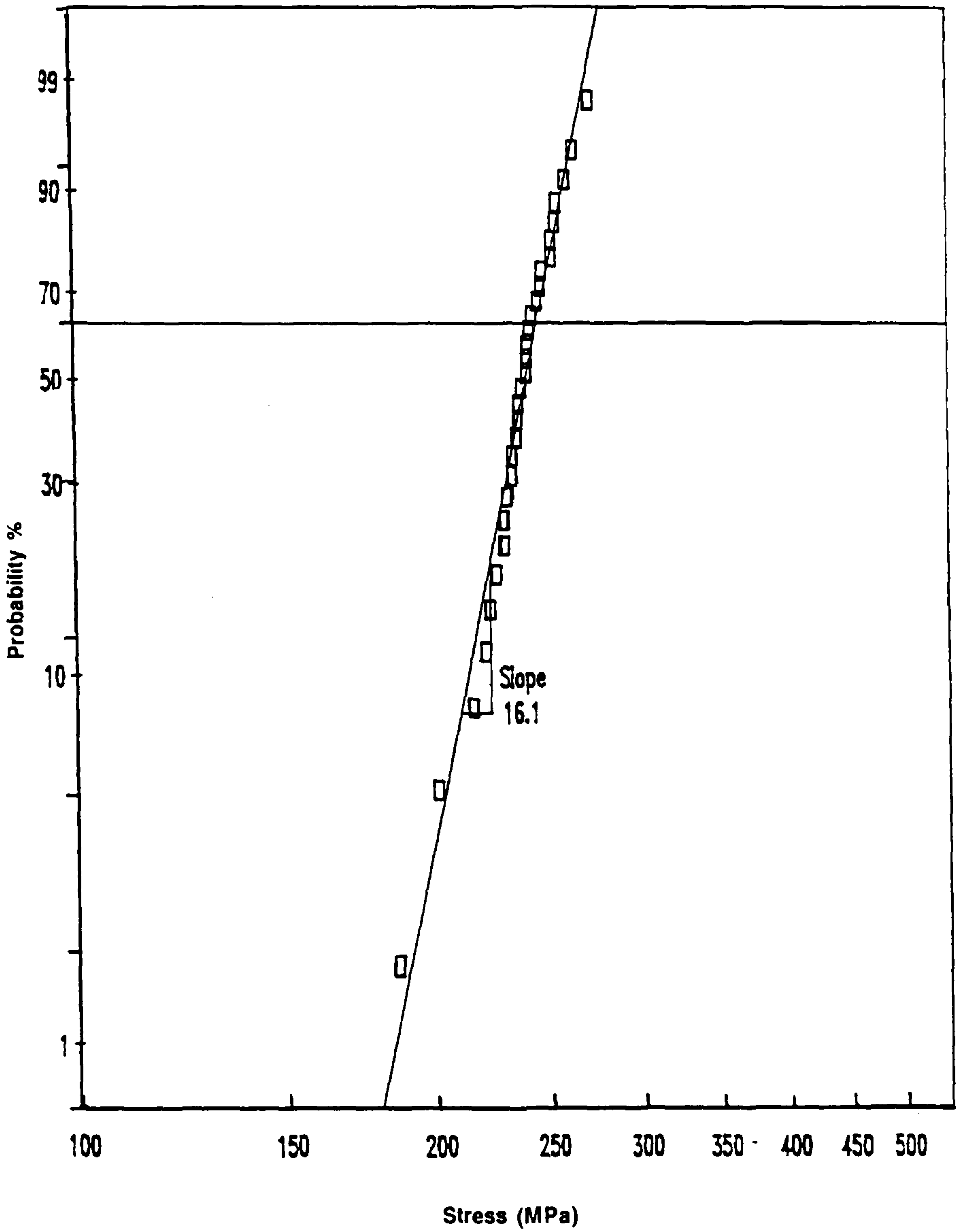


RBSN, 3 mm x 4 mm, 4 pt, Current Fixture, NPL (Morrell)

MATERIAL	RBSN	VINTAGE	
BILLET NO.		4-PT BEND (NPL "OLD" JIG)	
C.H SPEED	.5 mm/min	SPECIMEN SIZE	3X4 mm
TEMP	24 C	Characteristic Strength	
HUMIDITY	31.5%	of B.B	244 MPA
TESTER		SLOPE	16.08
MOMENT ARM	10 mm	CHART SPEED	N/A

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.	
105	N/A	4.0	3.0	185	26.9					2510
93	N/A	4.0	3.0	200	29.0					2510
81	N/A	4.0	3.0	215	31.2					2510
177	N/A	4.0	3.0	220	31.9					2510
153	N/A	4.0	3.0	222	32.2					2510
37	N/A	4.0	3.0	225	32.6					2510
45	N/A	4.0	3.0	229	33.2					2510
9	N/A	4.0	3.0	229	33.2					2511
117	N/A	4.0	3.0	230	33.3					2510
33	N/A	4.0	3.0	232	33.7					2511
33	N/A	4.0	3.0	232	33.7					2510
21	N/A	4.0	3.0	234	34.0					2510
141	N/A	4.0	3.0	235	34.1					2510
165	N/A	4.0	3.0	236	34.2					2510
201	N/A	4.0	3.0	237	34.3					2510
21	N/A	4.0	3.0	239	34.7					2511
45	N/A	4.0	3.0	239	34.7					2511
57	N/A	4.0	3.0	239	34.7					2511
57	N/A	4.0	3.0	240	34.8					2510
213	N/A	4.0	3.0	242	35.0					2510
9	N/A	4.0	3.0	245	35.5					2510
69	N/A	4.0	3.0	246	35.7					2510
129	N/A	4.0	3.0	247	35.8					2510
225	N/A	4.0	3.0	251	36.5					2510
206	N/A	4.0	3.0	251	36.5					2511
182	N/A	4.0	3.0	253	36.7					2511
158	N/A	4.0	3.0	254	36.8					511
170	N/A	4.0	3.0	259	37.5					11
194	N/A	4.0	3.0	263	38.1					2511
189	N/A	4.0	3.0	271	39.3					2510
				MEAN 237						
				STD 17						

RBSN, 3 mm x 4 mm, 4 pt, Current Fixture, NPL (Morrell)

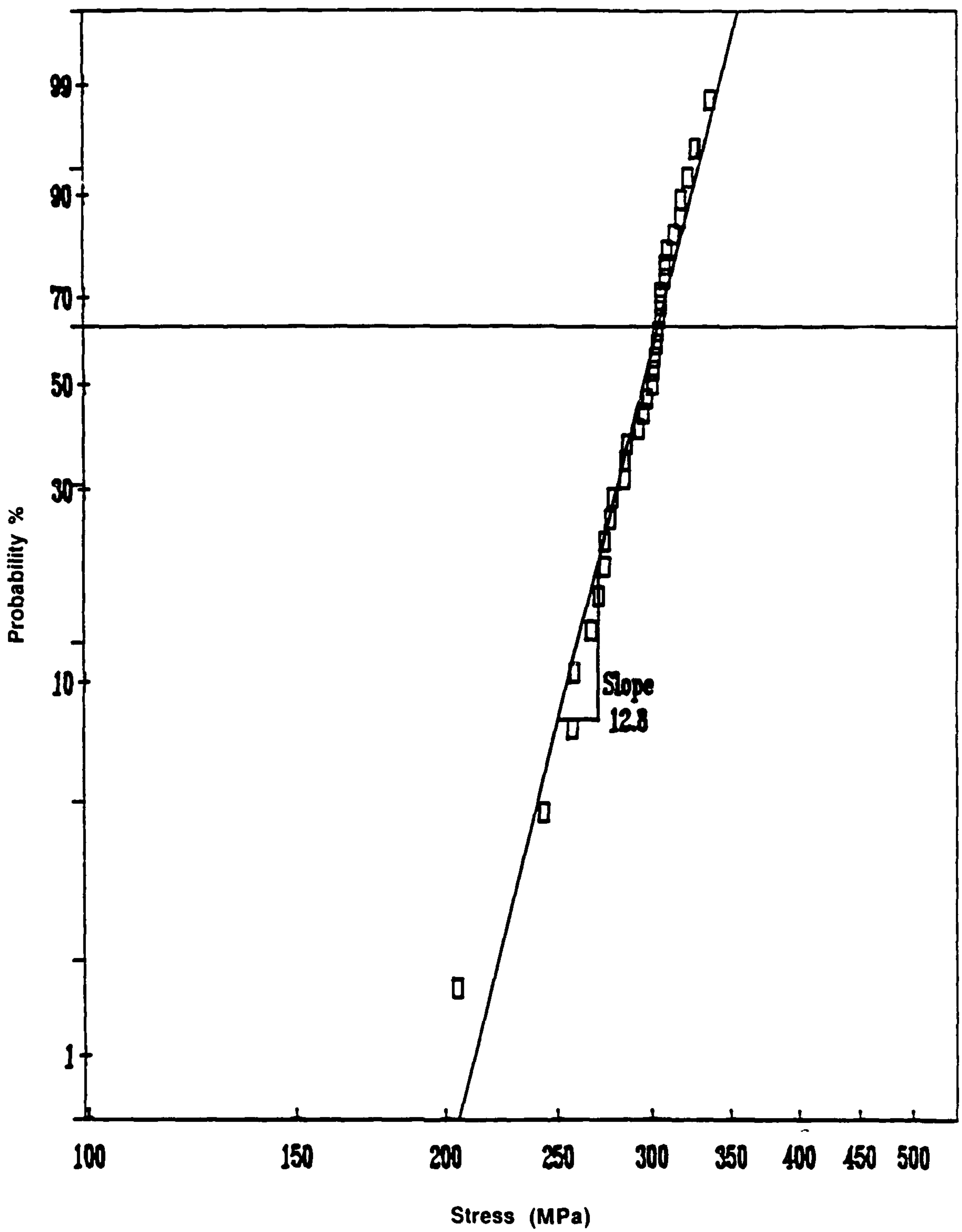


RBSN, 4.5 mm x 4.5 mm, 3 pt, Current Fixture, ARE (Godfrey)

MATERIAL	RBSN	VINTAGE	
BILLET NO.	2511	3 PT, ARE FIXTURE	
C.H SPEED	2.0 mm/min	SPECIMEN SIZE	4.5X4.5 mm
TEMP		Characteristic Strength	
HUMIDITY		of B.B	304 MPA
TESTER		SLOPE	12.79
MOMENT ARM	20 mm	CHART SPEED	

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
1	N/A	4.5	4.5	205	29.7				
2	N/A	4.5	4.5	243	35.2				
3	N/A	4.5	4.5	258	37.3				
4	N/A	4.5	4.5	258	37.4				
5	N/A	4.5	4.5	267	38.7				
6	N/A	4.5	4.5	271	39.2				
7	N/A	4.5	4.5	274	39.6				
8	N/A	4.5	4.5	274	39.6				
9	N/A	4.5	4.5	277	40.1				
10	N/A	4.5	4.5	278	40.3				
11	N/A	4.5	4.5	285	41.2				
12	N/A	4.5	4.5	285	41.2				
13	N/A	4.5	4.5	286	41.4				
14	N/A	4.5	4.5	293	42.4				
15	N/A	4.5	4.5	296	42.8				
16	N/A	4.5	4.5	297	43.1				
17	N/A	4.5	4.5	301	43.5				
18	N/A	4.5	4.5	301	43.6				
19	N/A	4.5	4.5	302	43.7				
20	N/A	4.5	4.5	303	43.9				
21	N/A	4.5	4.5	304	44.0				
22	N/A	4.5	4.5	305	44.2				
23	N/A	4.5	4.5	305	44.2				
24	N/A	4.5	4.5	305	44.2				
25	N/A	4.5	4.5	308	44.6				
26	N/A	4.5	4.5	308	44.6				
27	N/A	4.5	4.5	309	44.8				
28	N/A	4.5	4.5	313	45.3				
29	N/A	4.5	4.5	317	45.9				
30	N/A	4.5	4.5	317	46.0				
31	N/A	4.5	4.5	322	46.6				
32	N/A	4.5	4.5	326	47.3				
33	N/A	4.5	4.5	336	48.7				
				MEAN					
				292					
				STD					
				26					

RBSN, 4.5 mm x 4.5 mm, 3 pt, Current Fixture, ARE (Godfrey)

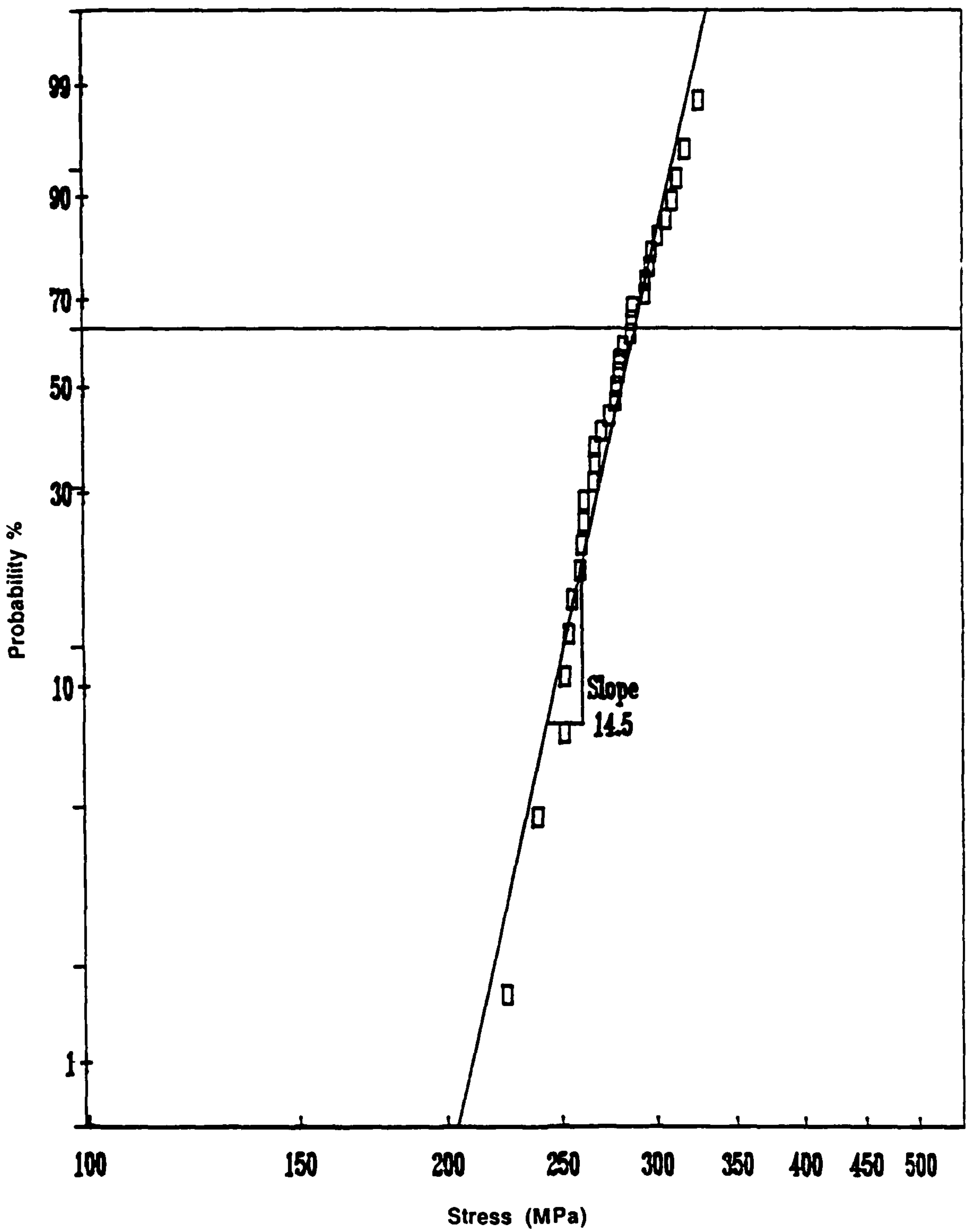


RBSN, 4.5 mm x 4.5 mm, 3 pt, Current Fixture, ARE (Godfrey)

MATERIAL	. RBSN	VINTAGE	
BILLET NO.	2510	3 PT, ARE FIXTURE	
C.H SPEED	2.0 mm/min	SPECIMEN SIZE	4.5X4.5 mm
TEMP		Characteristic Strength	
HUMIDITY		of B.B	288 MPA
TESTER		SLOPE	14.53
MOMENT ARM	20 mm	CHART SPEED	

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
1	N/A	4.5	4.5	224	32.5				
2	N/A	4.5	4.5	239	34.5				
3	N/A	4.5	4.5	251	36.4				
4	N/A	4.5	4.5	252	36.4				
5	N/A	4.5	4.5	254	36.7				
6	N/A	4.5	4.5	255	37.0				
7	N/A	4.5	4.5	259	37.6				
8	N/A	4.5	4.5	260	37.6				
9	N/A	4.5	4.5	261	37.8				
10	N/A	4.5	4.5	261	37.9				
11	N/A	4.5	4.5	266	38.5				
12	N/A	4.5	4.5	267	38.7				
13	N/A	4.5	4.5	267	38.7				
14	N/A	4.5	4.5	270	39.2				
15	N/A	4.5	4.5	275	39.8				
16	N/A	4.5	4.5	278	40.2				
17	N/A	4.5	4.5	278	40.3				
18	N/A	4.5	4.5	280	40.5				
19	N/A	4.5	4.5	280	40.5				
20	N/A	4.5	4.5	281	40.8				
21	N/A	4.5	4.5	286	41.4				
22	N/A	4.5	4.5	286	41.5				
23	N/A	4.5	4.5	287	41.5				
24	N/A	4.5	4.5	294	42.5				
25	N/A	4.5	4.5	294	42.6				
26	N/A	4.5	4.5	297	43.0				
27	N/A	4.5	4.5	297	43.1				
28	N/A	4.5	4.5	301	43.6				
29	N/A	4.5	4.5	306	44.4				
30	N/A	4.5	4.5	310	44.9				
31	N/A	4.5	4.5	313	45.3				
32	N/A	4.5	4.5	317	46.0				
33	N/A	4.5	4.5	326	47.2				
				MEAN					
				278					
				STD					
				23					

RBSN, 4.5 mm x 4.5 mm, 3 pt, Current Fixture, ARE (Godfrey)



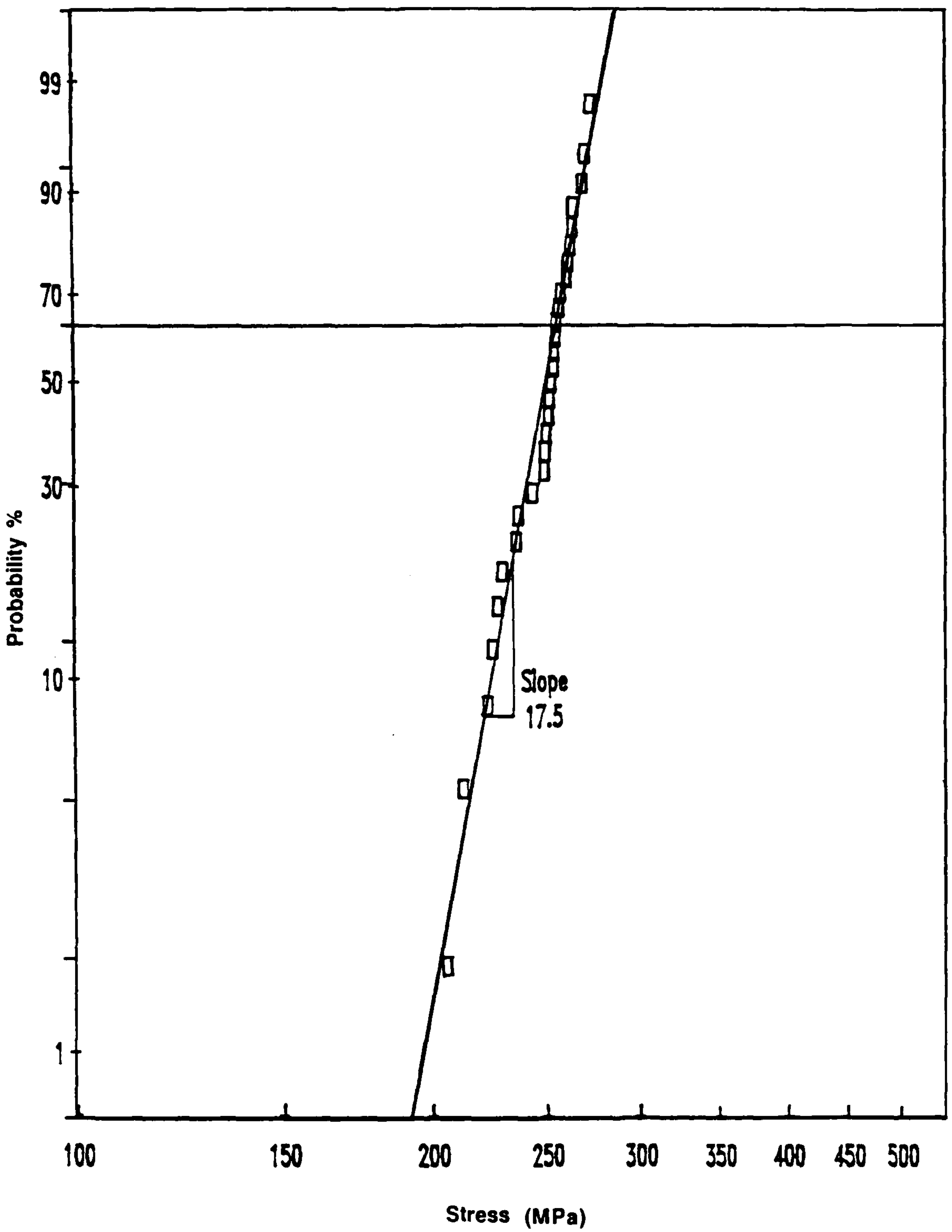
RBSN (Machined), 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), MTL (Quinn)

MATERIAL	RBSN (CUT SURF.)	VINTAGE	LOT 2511
BILLET NO.		1/4 POINT BEND	
C.H SPEED	.5 mm/min	SPECIMEN SIZE	MIL-STD B (3X4mm)
TEMP	74	Characteristic Strength	
HUMIDITY	33%	of B.B	255 MPA
TESTER	G. QUINN, MTL	SLOPE	17.46
MOMENT ARM	10 mm	CHART SPEED	100mm/min

===

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.	
102	249.0	4.019	3.006	206	29.8		NO	NO		2511
93	253.5	4.029	2.983	212	30.8		NO	NO		2511
66	267.5	4.034	2.991	222	32.3		NO	NO		2511
69	272.0	4.034	3.001	225	32.6		NO	NO		2511
111	275.5	4.032	3.006	227	32.9		NO	NO		2511
78	278.0	4.030	3.007	229	33.2		NO	NO		2511
144	286.0	4.031	3.007	235	34.1		NO	NO		2511
96	284.0	4.026	2.992	236	34.3		NO	NO		2511
147	295.0	4.026	3.008	243	35.2		NO	NO		2511
99	300.0	4.030	2.998	248	36.0		NO	NO		2511
72	302.0	4.032	3.005	249	36.1		NO	NO		2511
132	303.5	4.029	3.008	250	36.2		NO	NO		2511
63	304.0	4.033	3.002	251	36.4		NO	NO		2511
108	305.5	4.031	3.007	251	36.5		NO	NO		2511
117	306.0	4.028	3.006	252	36.6		NO	NO		2511
138	307.5	4.029	3.007	253	36.7		NO	NO		2511
105	306.5	4.031	3.000	253	36.8		NO	NO		2511
81	308.5	4.029	3.007	254	36.8		NO	NO		2511
135	309.0	4.031	3.008	254	36.9		NO	NO		2511
126	309.5	4.032	3.001	256	37.1		NO	NO		2511
75	311.0	4.028	3.003	257	37.3		NO	NO		2511
150	313.5	4.028	3.000	259	37.6		NO	NO		2511
141	316.0	4.032	3.005	260	37.8		NO	NO		2511
129	316.5	4.029	3.002	262	37.9		NO	NO		2511
114	317.0	4.029	2.999	262	38.1		NO	NO		2511
84	319.5	4.026	3.008	263	38.2		NO	NO		2511
87	325.5	4.028	3.009	268	38.8		NO	NO		2511
123	326.0-	4.031	3.003	269	39.0		NO	NO		2511
90	329.5	4.027	3.008	271	39.3		NO	NO		2511
				MEAN						
				248						
				STD						
				17						

RBSN (Machined), 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), MTL (Quinn)

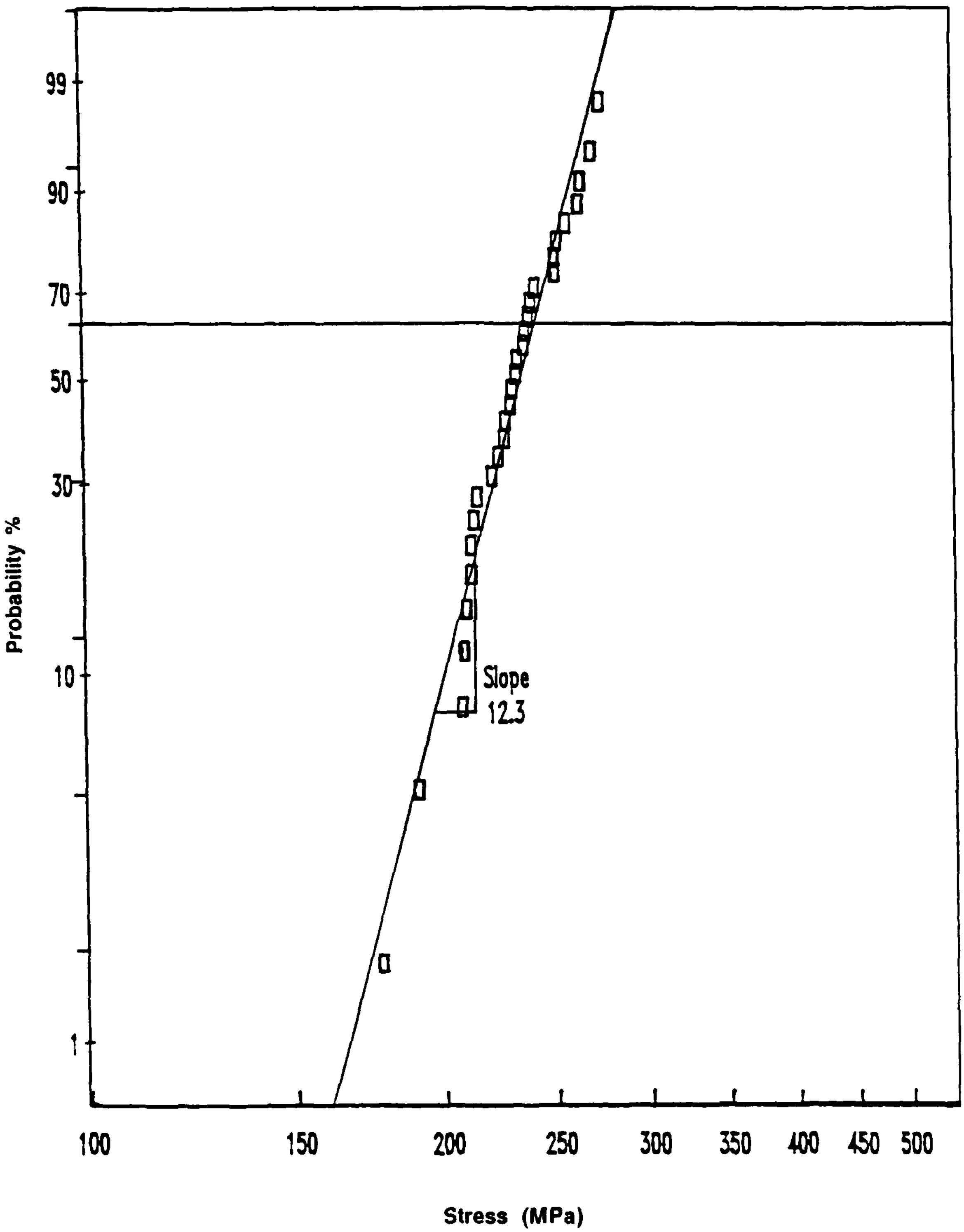


RBSN (Machined), 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), NPL (Morrell)

MATERIAL	RBSN	VINTAGE	
BILLET NO.		1/4 POINT BEND	
C.H SPEED	.5 mm/min	SPECIMEN SIZE	MIL-STD B (3X4 mm)
TEMP	26 C	Characteristic Strength	
HUMIDITY	36%	of B.B	241 MPA
TESTER		SLOPE	12.26
MOMENT ARM	10 mm	CHART SPEED	N/A

SPEC ID	LOAD N	WIDTH mm	HEIGHT mm.	STRESS MPA	STRESS KSI	FLAW CODE	PHOTO Y/N	SEM Y/N	MISC.
22	N/A	4.0	3.0	177	25.7				
1	N/A	4.0	3.0	190	27.6				
25	N/A	4.0	3.0	207	30.1				
12	N/A	4.0	3.0	208	30.2				
27	N/A	4.0	3.0	209	30.4				
20	N/A	4.0	3.0	211	30.6				
3	N/A	4.0	3.0	211	30.7				
26	N/A	4.0	3.0	213	30.8				
28	N/A	4.0	3.0	214	31.0				
8	N/A	4.0	3.0	220	32.0				
29	N/A	4.0	3.0	224	32.4				
14	N/A	4.0	3.0	226	32.8				
5	N/A	4.0	3.0	227	32.9				
11	N/A	4.0	3.0	229	33.2				
10	N/A	4.0	3.0	230	33.3				
24	N/A	4.0	3.0	231	33.6				
16	N/A	4.0	3.0	232	33.6				
23	N/A	4.0	3.0	235	34.1				
15	N/A	4.0	3.0	236	34.2				
2	N/A	4.0	3.0	237	34.4				
17	N/A	4.0	3.0	238	34.5				
19	N/A	4.0	3.0	240	34.8				
30	N/A	4.0	3.0	250	36.3				
13	N/A	4.0	3.0	250	36.3				
6	N/A	4.0	3.0	251	36.5				
9	N/A	4.0	3.0	256	37.1				
21	N/A	4.0	3.0	263	38.1				
7	N/A	4.0	3.0	264	38.2				
4	N/A	4.0	3.0	269	39.1				
18	N/A	4.0	3.0	274	39.7				
				MEAN					
				231					
				STD					
				22					

RBSN (Machined), 3 mm x 4 mm, 4 pt, MIL-STD-1942 (MR), NPL (Morrell)



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George D. Quinn

Technical Report MTL TR 89-62, July 1989, 132 pp-illus-tables, D/A Project: 278012.12

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Silicon nitride
Alumina

A mechanical testing round robin exercise was performed under the auspices of The Technical Cooperation Program (TTCP). TTCP is a collaboration between the defense establishments of Australia, Canada, New Zealand, the United Kingdom, and the Unites States. TTCP coordinates and shares results from research activities. The work reported was performed by panel P-TP-2, Ceramic Materials, and was concluded in 1987. Flexural strength at room temperature was measured for a sintered alumina and a reaction-bonded silicon nitride. These tests are relevant to advanced structural ceramics. The goal of the exercise was to determine if accurate and consistent results could be obtained by the participants using various test procedures. The round robin was a success, and most issues raised were unequivocally answered. The sintered alumina and reaction-bonded silicon nitride were quite satisfactory for the exercise. Flexure strengths measured by seven laboratories using the U.S. Army MIL-STD-1942 procedure were, for the most part, quite consistent. A specimen configuration with a 2:1 cross-section ratio also gave good results. Older practices and procedures gave less consistent, and possibly erroneous, results.

U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
FLEXURE STRENGTH OF ADVANCED CERAMICS - A ROUND ROBIN EXERCISE -
George D. Quinn

Technical Report MTL TR 89-62, July 1989, 132 pp-illus-tables, D/A Project: 278012.12

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Key Words

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